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A STEP TOWARD TYPE SYNTHESIS USING
THE UNITED STATES PATENTS

A THESIS

Presented to

The Faculty of the Graduate Division

by

Sterling Russell Brown

In Partial Fulfillment

of the Requirements for the Degree

Master of Science in Mechanical Engineering

Georgia Institute of Technology

February, 1968

A STEP TOWARD TYPE SYNTHESIS

USING THE UNITED STATES PATENTS

Approved: ______________________

Chairm ______________________

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Date approved by Chairman: 2/12/68

ACKNOWLEDGEMENTS

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

SUMMARY

The field of kinematics provides a very large number of unique kinematic chains. Except for some of the simplest types, however, the functions that they are able to perform and the uses that can be made of them are unknown. The approach to a solution of this problem presented here is based on discovering the functions mechanisms have performed in the past. A pilot scheme has been developed to find and record linkwork from the United States patents. These records are incorporated in an information storage and retrieval system. The use of a function vocabulary and other coding designators make it possible to express design requirements in terms of search requests to the retrieval system. In this way functions are correlated with kinematic chains while providing the designer with an aid to type synthesis.

CHAPTER I

INTRODUCTION

Modern kinematics is considered to have begun with the work of Reuleaux in 1875. Since that time a great deal has been done concerning the design and analysis of mechanisms. Until recently, however, analysis had received most of the attention. This situation is rapidly being corrected.

At the present time kinematic design from the synthesis point of view is approached through three phases. These are type synthesis, structural analysis, and dimensional synthesis. During the type synthesis phase, the form of the mechanism is decided upon. This means choosing the kind of links or construction units to be used, such as gears, cams, linkwork, belts and pulleys, chains, or something else of this nature. (These units are also used in combination.) Structural analysis is concerned with determining the number of links and the nature of the connections between them, necessary to give the mechanism the desired mobility. Dimensional synthesis is the process of determining the dimensions of the parts of a mechanism to meet the requirements of a specific application (5).

While all these processes deal with mechanisms in general, much can be said when only considering linkwork, or linkwork in combination with gears and cams. In this area dimensional synthesis has received extensive study; structural analysis has been given an adequate amount;

type synthesis, however, has received very little.

Type synthesis holds an important position as the first of the three design phases. It can not be approached rationally, however, without a thorough understanding of all the stages that follow it. Also during the type synthesis stage many other factors must be considered which lie outside the field of kinematics. Some of these are the materials involved, methods of manufacture, operating space, maintenance, and power sources (5). These are just a few factors, for there can be an extremely large variety. Their number and order of importance are determined by the specific application being considered. Even in this vast variety of requirements one area of consideration must be satisfied or the final result will be of no value. This is the function that the mechanism will be called on to perform and the final use that will be made of the design.

The present state of structural analysis gives ample information about the variety of kinematic chains that exist. Unfortunately in all but the simplest cases, the functions that these kinematic chains can perform as mechanisms are unrecorded. Because of this the designer is confronted with an unlimited number of kinematic chains. Without knowing the functions they can perform, he has virtually no idea which are able to meet the requirements of his specific application (3). Therefore, before a reasonable selection of mechanism construction unit in general can be made, information concerning the functions which linkwork mechanisms can perform is needed.

Two approaches toward a solution of this problem are suggested by Davies (3). One involves fundamental research into the kinematics of each structural form linkwork can have. The other concerns the collection of functions that linkwork has performed in actual past practice.

The first approach is now being pursued by some researchers through detailed mathematical analysis of output motions. The output motions of some simpler mechanisms are being analyzed in terms of their Fourier coefficients. Studies of coupler curves from kinematic chain inversions are also being made (3).

The second approach, that of collecting and digesting the information obtained from past linkwork, would seem to yield results more quickly. This task of gathering together the practical experience of designers might be most profitably accomplished by means of a search through patent records. A workable plan based on the United States Patents is the subject of the following chapters.

While seemingly less elegant than the fundamental research approach, the development of a function collection would have unique and immediately useful results. Using information storage and retrieval techniques, mechanism functions could be correlated with kinematic chains and the mechanisms to which they belong. The function correlation would become more complete as the collection of analyzed mechanisms grew. Properly developed such a system would also be a useful aid to the designer practicing type synthesis. Design requirements and ideas could be translated into search requests for the system. The appropriate mechanisms and kinematic chains would be given as answers to the search requests. This service would be immediately available from the system. Its effectiveness would increase with the growth of the correlation between mechanism functions and kinematic chains.

The system could also be useful in discovering the needs of practicing designers. This information could then help guide fundamental research in new directions.

The following development of the system just described, while in no way discounting other approaches, does offer a fresh and practical aid to the problem of type synthesis.

CHAPTER II

HISTORICAL DEVELOPMENT

1. Review of Literature

Before presenting a specific approach as an aid to type synthesis, it will be helpful to look at classification systems in general and to review some previous work dealing with type synthesis and classification of mechanisms.

Classification can be thought of as a search for order. It implies a systematic grouping of objects, elements, etc., showing a relationship of one thing to another or to a group of things. One important effect of a classification system has a direct relation to type synthesis: This is the help which it could give to a designer in finding forms and arrangements of mechanisms best suited to fulfill certain specifications (5).

Among past work, two types of classification system dealing with mechanisms may be recognized. These are the structural and the functional. The structural system deals with the nature or characteristics of the constituent <u>parts</u> of a mechanism. Various forms of the system result from considering the different characteristics of the parts, their number, geometrical arrangement, the types of connections between them, and their relative motions (5).

The functional classification system is concerned with the <u>complete</u> mechanism and its function (5). Such a system considers the mechanism as a unit, capable of transforming a given input motion into another output. The results of this capability are used in classifying the mechanism. Variations of this system are the result of different ideas of what is meant by the function of a mechanism. Some classifications have used the transformation itself while others have considered the motions and tasks performed by the mechanism's output. In a functional classification system Hartenberg and Denavit (5) suggest that the mechanism is treated as a "black box," receiving one kind of motion as an input and producing another as an output. The classification scheme is then concerned with what the black box does.

One of the earliest approaches to a structural classification system was made by Willis (18) in 1841. Willis established his system on "relations of motion" and was concerned with the manner in which the motion transformation between input and output members was achieved (5). He states his purpose in the preface of Principles of Mechanism (18). "The first ground of my classification ... is the mode in which the motion is transmitted.... These modes I have divided into Rolling and Sliding Contact, Link-Work, Wrapping Connection, and Reduplication." The work of Reuleaux went much further: He was concerned with the connection between immediately neighboring parts and not the complete input-output relation. Reuleaux introduced the concepts of lower and higher pairs (15) and considered the particular and unique motion restrictions imposed by the shapes of the surfaces in contact (5).

The other or functional type of classification system has been used for a longer period of time. This is because it is concerned with the complete mechanism and its purpose. Since the very beginning, mechanisms have been classified with respect to the tasks they could perform.

Pollio Marcus Vitruvius used the functional classification system as early as the first century B.C. His "De Architectura" included mechanical and military engines. The work of Hero of Alexandria in the first century A.D. can also be considered as following a functional system (5) (18). Some later authors only considered machines used for one particular kind of work. Valturius (1472) was concerned with war machinery and Agricola (1550) with machinery for mining and metal-working. Other works presented collections of machines classed and described with reference to the functions for which they were constructed. These were divided, for example, into machines for raising water, grinding flour, sawing timber, and the like. Such classifications are given in the works of Besson (1569), Ramelli (1580), Strada (1618), Zonca (1621), Branca (1629), and Bockler (1662). The Theatrum Machinarum (1724) of Jacob Leupold makes the first reference to machinery in kinematic terms. His work has chapters dealing with "cams," machines for "converting a circular motion into a rectilinear," or a "back-and-forwards motion," and for converting a "back-and-forwards motion into a continued circular motion." (18)

Gaspard Monge, one of the principal founders of the École Polytechnique, proposed setting aside two months of the first year of study for what he called the "elements of machines." In the words of Monge, "The most complicated machines being merely the result of a combination of some of these elements, it is necessary that a complete enumeration of them should be drawn up." Monge used this enumeration in his lectures.

Later his enumeration became the basis for two similar systems, one of Hachette and the other of Lanz and Bétancourt. "An Essay on the Composition of Machines" (1808) was the Lanz and Bétancourt system in the form finally adopted by the École Polytechnique. The system is described in the beginning of the work:

> The motions of the parts of machines are either (1) rectilinear, (2) circular, or (3) curvilinear; and each of these may be continuous in direction or alternate, that is back and forward. These six motions admit of being combined two and two in twenty-one different ways, each motion being supposed to be also combined with itself. The object of every simple machine being to counterchange or communicate these motions, the following system will include them all. (18)

The work included tables of input-output transformations and sketches of mechanisms capable of performing them.

A more comprehensive and complete attempt was made by Borgnis in 1818 (18). The same functional type of classification has continued into more recent times. G. Van der Haeghen lists 762 mechanisms in his Les Mouvements Mécaniques (about 1936) with respect to their input-output motion transformations. Jones in Ingenious Mechanisms for Designers and Inventors favors more of a "black box" classification, with detailed descriptions of each mechanism. A Practical Theory of Mechanisms (1947) by Grodzinski deals with input-output relations along the lines of Lanz and Bétancourt's work. The functional classification system has been carried a step farther by Davies (3) with suggestions concerning different approaches for both the researcher and designer to follow. The present work is an application of some of these ideas. The most recent contribution has been made by Tuttle (17) in molding his type synthesis suggestions into a functional classification scheme. The work, aimed at the designer, covers a broad range of material with clarity and good advice. Superfluous detail is removed to expose fundamental concepts, but there is a tendency toward over-simplification.

Little has been said by anyone of mechanisms with two or more inputs and, as a result, two or more degrees of freedom. Information recorded from the United States patents indicates their varied usefulness and considerable importance. The frequent occurrence of two-input mechanisms and some with three inputs is notable. Hydraulic cylinders are used a great deal as actuators in these cases. Usually the application requires large input forces. Much needs to be done with multiple mobility mechanisms, and the works of Davies (2), Hain (9), and Manolescu (13) (14) have given a good foundation.

2. Reuleaux's System of Structural Classification

Willis and Reuleaux each represented a reaction in thought to the previous development of kinematics. Before them kinematics had been approached almost entirely from a functional classification sense. No founding principles had really been discovered, and mechanisms were classified using as many techniques as authors. Redtenbacher, a professor and early teacher of Reuleaux, even expressed a belief that no true science of the study of mechanisms was possible, because "they could be arranged only according to their practical usefulness, and for the rest must be treated mathematically." Reuleaux was searching for "the very simplest elements" upon which the science of kinematics could be built. He was not critical of the idea of a functional system, but of the way the functional system had previously been employed.

> The real cause of the insufficiency of the system is not, however, the classification itself; it must be looked for deeper. It lies, as I have already pointed out, in the circumstance that investigations have never been carried back far enough, — back to the rise of the ideas; that classification has been attempted without any real comprehension being obtained of the objects to be classified. (15)

Reuleaux considered a classification system as secondary to the development of kinematics from its simplest elements. He expresses this and a goal still relevant today in the following statement:

> When however its (kinematics') investigations enable it to furnish the means of producing any required kind of motion, it will begin to deserve the name of Science. It will then itself point out the true classification of its own material. (15)

Reuleaux did carry his investigations back to the rise of the ideas, the "simplest elements." After laying down the founding principles of kinematics he was able to propose a structural classification system made up of "constructive elements." These were parts which occurred with special frequency in machine construction. Such constructive elements had been considered before by many writers on machine design. Reuleaux, however, formed a classification for these constructive elements based for the first time upon their true kinematic nature. This structural classification was made up of six classes of mechanical components (15). Reuleaux's six groups are even today capable of accounting for all the components from which mechanisms and machines are built (5). Reuleaux's six groups are:

1. The eye-bar type of link, called crank in kinematics
2. The wheel, including gears
3. The cam in its many forms
4. The screw for communicating motion and force

5. The intermittent-motion devices called ratchets

6. The tension-compression organs, or parts having "one-way rigidity" (5)

Figures 1 and 2 contain examples of these mechanical components.

3. Recent Examples of Functional Classification Systems

The system of Lanz and Bétancourt, preceded by Monge, has continued to be modified. When used with an understanding of Reuleaux's founding principles (15), such a functional system can consolidate kinematic ideas and simplify the selection of design approaches.

Table 1 from Grodzinski (8) illustrates a modified Lanz and Bétancourt scheme. Davies (3) suggested that such a system might be useful as a large scale help to designers when incorporated into an information storage and retrieval system.

Tuttle's book Mechanisms for Engineering Design (17) is concerned with the designer's selection of a suitable approach in the design of a mechanism, including linkwork. The functional capabilities of a large number of mechanisms are presented with emphasis on the basic principles and characteristics of the motions produced. To make this material available to the designer a functional classification system was used. Tuttle states, "the technique of classification according to output motion was adopted." The output motion is considered to be described by a point moving along a path. For such a case, Tuttle suggests "the form and extent of the path plus changes in velocity along the path will describe the motion." He uses words such as circular, rectilinear, and random to describe the shape of the path. Intermittent, irregular, dwell, or continuous describe the velocity. "Semifixed" refers to

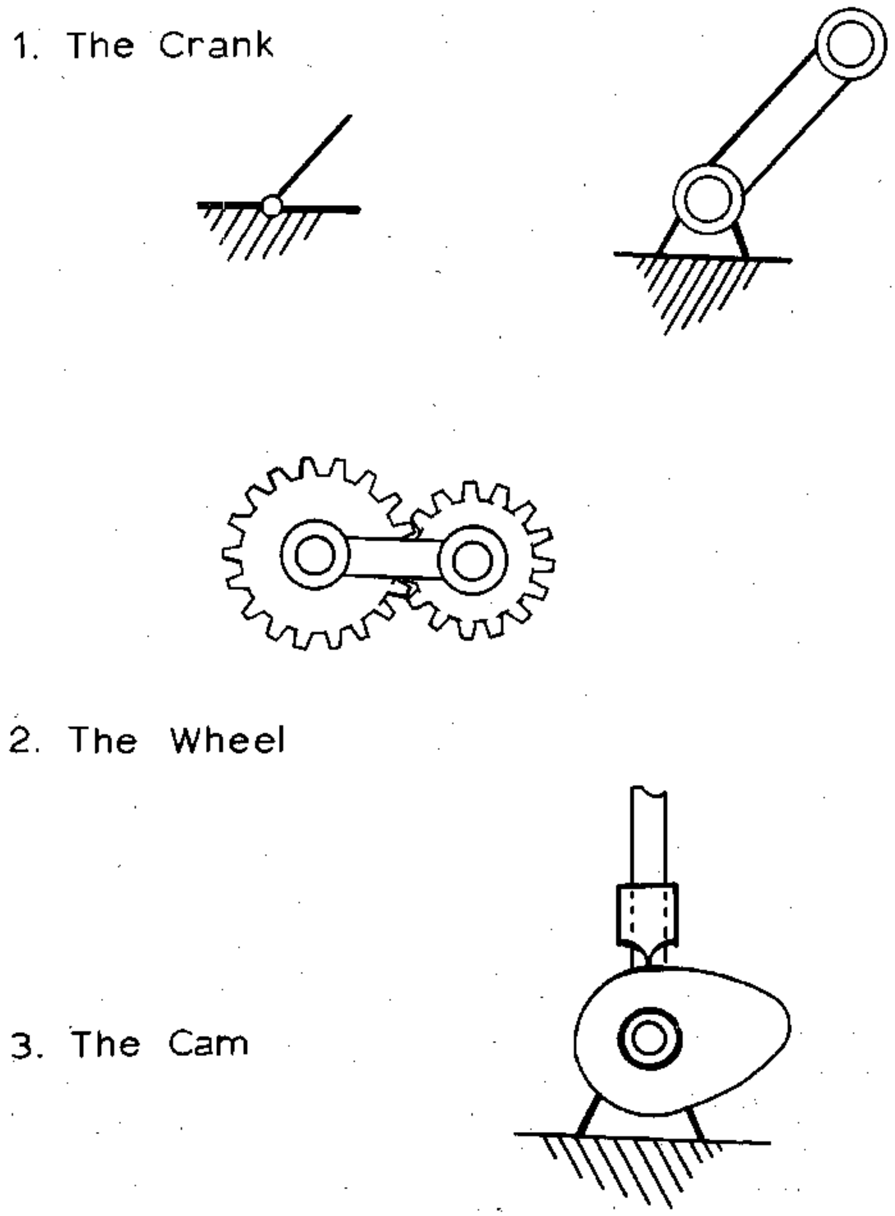


Figure 1. The Crank, Wheel, and Cam of Reuleaux's Six Groups.

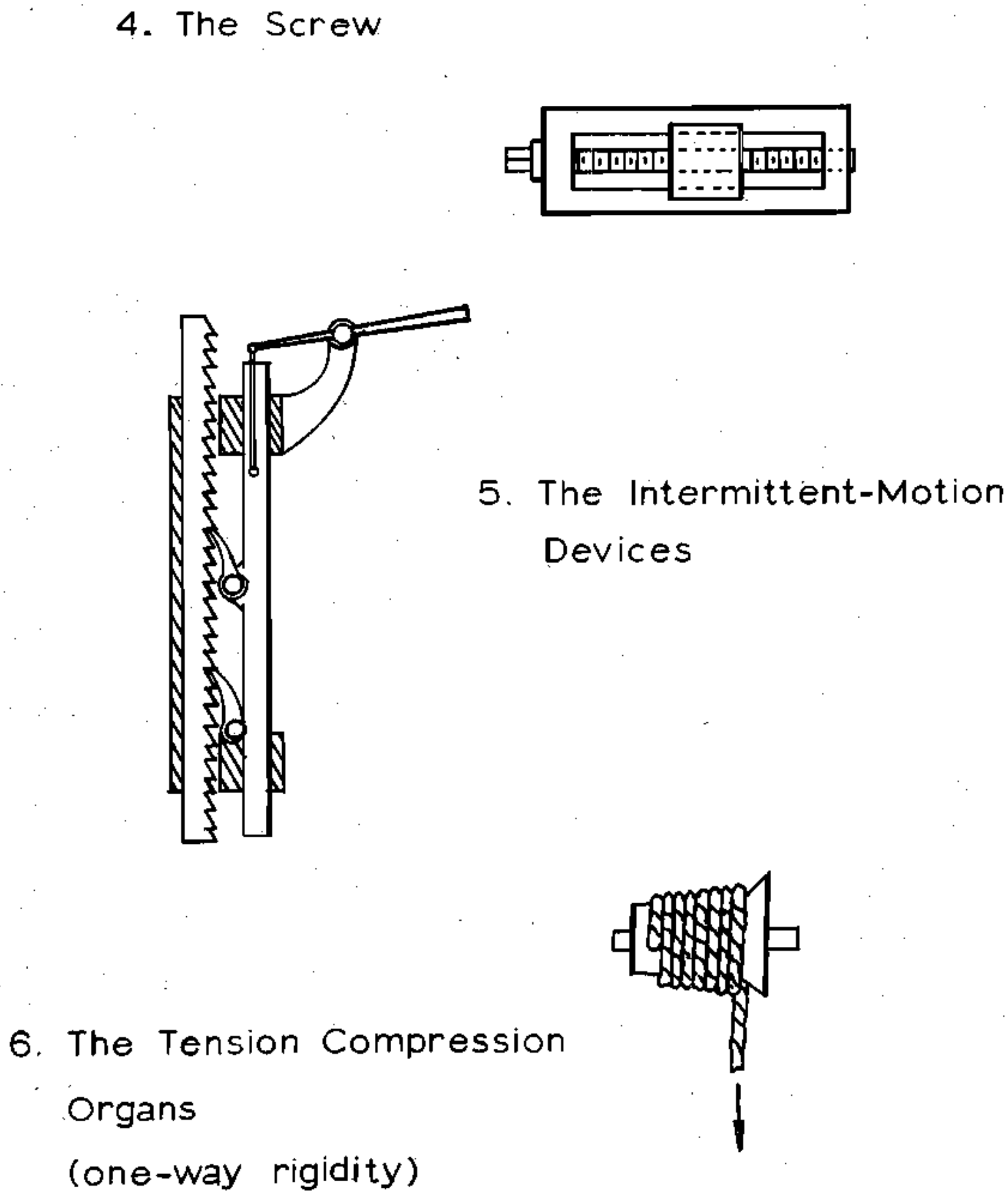


Figure 2. The Screw, Ratchets, and Tension-Compression Organs of Reuleaux's Six Groups.

Table 1. A Survey of Mechanisms from Grodzinski (8)

			Driven motion for uniform driving motion				Transmission ratio				Position of axis or direction of movement						
								Variable									
			Uniform	Non-uniform	Interrupted	Reversible	Constant	When stationary	During running	Infinitely	Great	Co-axial	Parallel	Intersection	Moving	Guiding	Safe against shock loads
Driven	Driving		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Rotating	Rotating	A	A1	A2													
	Reciprocating	B	B1	B2													
Swinging over 120 deg.	Rotating	C															
	Reciprocating	D															
Swinging (in an arc)	Rotating	E															
	Reciprocating	F															
Reciprocating (straight line)	Rotating	G															
	Reciprocating	H															
Reciprocating (curvilinear course)	Rotating	J															
	Reciprocating	K															

mechanisms having no relative motion between elements of their structure. The classifications used are:

1. Motion-Circular-Continuous
2. Motion-Circular-Intermittent
3. Motion-Circular-Irregular
4. Motion-Rectilinear-Intermittent
5. Motion-Random-Toggle
6. Motion-Semifixed-Locate, Latch or Lock
7. Motion-Semifixed-Flexural Mechanisms

In Chapter 5 Mr. Tuttle makes the statement, "It is impossible to catalog linkage systems according to their functional output." It is hoped that this thesis will show that such tasks are possible.

CHAPTER III

THE UNITED STATES PATENTS

In order to use any form of collected data in the most effective manner, it is necessary to understand as much about its generation and collection as possible. The United States patents present such a set of data in the form of an accumulated record of engineering design experiences. It is the purpose of this chapter to present sufficient information concerning the patents in order that it will be clear from whom and in what manner the information they contain is generated. This background is used as a foundation for evaluating their kinematic usefulness and presenting an effective method of search for linkwork applications.

1. Beginning

The first United States patent was issued on July 31, 1790, to Samuel Hopkins for an improvement in "the making of Pot ash and Pearl ash by a new Apparatus and Process." (16) Since that time approximately 3,400,000 other patents have been issued. Today they are being granted on an average of 1000 per week. A patent grants the inventor the right to exclude others from making, using, or selling his invention. This right is granted by the United States government for a period of 17 years (7).

2. Patentable Material

The general field of subject matter that may be patented is specified by law. The statute states that a person who "invents or discovers any new and useful process, machine, manufacture, or composition of matter, or any new and useful improvements thereof, may obtain a patent." The term "useful" as used in the statute requires that the subject matter have a useful purpose and be able to operate in order to perform this purpose. The term "manufacture" refers to all manufactured articles (7).

3. Systematization of Patents

Because of the broad field of subject matter involved, definite categories have been formed within the patent system. The system is organized into design, plant, and trademark categories, along with those of an electrical, chemical, and general and mechanical nature (10).

Design patents are granted "to any person who has invented any new, original and ornamental design for an article of manufacture." The patent is only concerned with the shape of the article and not its composition or uses (7). Since 1930 plant patents have been granted to developers or discoverers of new and distinct varieties of plants. The word plant is used in the botanical sense (12). Trademarks, as far as the patent office is concerned, relate to the name or symbol used with goods to indicate their origin. These trademarks used in interstate or foreign commerce are patentable (7).

All remaining patentable material is contained in the chemical, electrical, and general and mechanical classes. These three sections receive the largest portion of each week's patents.

4. Kinematic Usefulness of Patents

A main part of the work of this thesis is concerned with development of a method of gathering the accumulated knowledge of machine designers and digesting it with respect to a particular part of its kinematic value. This particular part of interest is linkwork and linkwork in combination with gears and cams. The digestion is concerned with gaining sufficient information about a mechanism's structure, functions, special characteristics, and other properties to incorporate it into an information storage and retrieval system. The United States patents are very useful in these respects, being the collection of a large number of designs presented in a standard form. The separation of the entries into technical categories helps with the searching problem. The strict requirements on content of the written matter, the close standards of form and presentation imposed on the drawings, and the screening with respect to a set of unvarying prerequisites by the examiners all add to the value of the information obtained.

The kinematic usefulness of two particular parts of a patent, the detailed description and the claims, require special attention.

Every patent contains a detailed description of its invention. This description is required to be in such clear and precise terms that any person skilled in the art to which the invention pertains will be able to make and use it (7). The description is incorporated with drawings to accomplish this purpose. The detailed description can be of kinematic importance in helping determine a complicated or unclear mechanism's properties and structure.

The claims are the heart of a patent and state exactly for what particular features the inventor seeks patent protection (12). They are the operative part of the patent. It is by the claims that novelty and patentability are judged (7). Their kinematic usefulness, however, is limited.

The claims apply to the invention as a whole. However, linkwork mechanisms are very rarely the object of the entire patent, as is indicated by the broad wording of the statute defining patentable material and from actual experience with the patents. The linkwork applications are usually found incorporated in the design of the patented machine, process, or manufactured article. Because of this, the opportunity to use the information of the claims kinematically seldom occurs.

The claims that could be used are limited in other ways. A claim must always be written in terms of detailing or describing a structure. This structure is the object of the patent for which the inventor seeks patent protection. The inventor can not patent the function or purpose of his invention. If this were possible, the inventor of the first potato peeler could have made the claim, "means for peeling potatoes." As a result, all other inventors of structures or devices for peeling potatoes would be infringing this previous patent and subject to prosecution. Instead such patents usually begin, "A potato peeler comprising ... ," followed by details and descriptions of the device. This allows to the inventors of all other potato peelers, not "comprising" similar or closely related structures, the opportunity for a patent. A claim which only states an invention's function or purpose and which would have the effect of patenting that function or purpose, is called a "functional claim." Such a claim is immediately rejected by the Patent Office (12).

Although desirable because it protects future inventors, this disallowance of the functional claim makes it impossible for a mechanism's function to be deduced from the claims of a patent alone and so used in kinematic classification (12). For the purpose of classification such a claim would be helpful, since the kinematic and Patent Office meanings of the word "function" are closely related. Kinematically a new potato peeler's function might be described as "peeling"; the Patent Office idea of function would be "peeling potatoes," a more specific and purpose related statement. The functions of inventions still exist, however, and are very useful kinematically in connection with a function vocabulary.

The patent attorney indirectly adds to a claim's kinematic limitation. One responsibility of the attorney is to make a patent's claims as broad as will be allowable by the examiner. The broader and less specific the claims, the stronger and more valuable the patent will be to the inventor. This tendency toward breadth, coupled with the legal language used in their wording, makes the claims still poorer indicators of a mechanism's functions, properties, or structure.

A representative claim from United States patent 3,306,571 is shown below. The corresponding mechanism is drawn in Figure 3.

> Gate-valve having an obturating member which is adapted to move within a conduit from a longitudinal position to a transverse position so as to effect at will the obturation of said conduit irrespective of the direction of the forces exerted on said obturating member by the fluid which is present within said conduit, said gate-valve comprising a valve body ... and means for guiding and operating the flap so as to permit said flap to move between a position in which it is located parallel to the axes of both valve seats and one of the positions in which said flap is applied against one ... valve seat.

5. Methods for Finding Linkwork Applications

The classification system used by the United States patents is based on classes and subclasses. Three-hundred and fifty-two classes or main groupings are broken down into some 63,000 subclasses (11). Each class and its modifying subclasses are given code numbers and definitions. Every new patent is classified according to this system, while many old patents must be reclassified each year.

There are two approaches available for finding linkwork applications in the patents. One is to search an area of probable linkwork application using the Patent Office Classification System. The other is to consider a certain time period and study each patent within a broad section.

Using the first approach, a specific area of search or probable location of linkwork application is decided upon. The class and subclasses corresponding to this specific area are selected using the Patent Office Classification System's class and subclass definitions. The class and subclasses are then searched. It is usually found that the corresponding patents are dispersed through a large volume of material and not easily accessible. A great deal of time is required for profitable returns from such a search technique.

The other approach of studying each patent within a selected time period for linkwork applications would seem to be a monumental task. Each patent consists of one to sometimes twenty or more drawings. These are followed by pages of written matter which include the previously described detailed description and claims.

The time involved using such a search technique would be excessively long except for the weekly publication of the Patent Office, the "Official Gazette."

The Official Gazette is the first public disclosure of new inventions. It is issued every Tuesday, the same day patent grants are issued (10). The new patents are placed in one of four sections in this order:

General and Mechanical

Chemical

Electrical

Designs

Within each section the patents are listed in numerical order according to their class and subclass. One representative drawing is published in the Official Gazette for each illustrated patent. One or two of the patent's significant claims are listed. Also for each patent the Official Gazette publishes the patent number, title of the invention, the inventor, the inventor's country of residence, the assignee, filing date of the application, the total number of claims, and the class and subclass.

By first studying the Official Gazette, the patents can be efficiently screened with respect to their kinematic value. Clear linkwork applications can be seen immediately and recorded. More complicated applications can be recognized and their complete patents referred to for clarification. Suspected or probable uses of linkwork can also be noted and later reference made to their complete patents for positive determination. The use of such a search technique has proven to be both efficient from a time standpoint and productive with regard to useful linkwork applications. The results of the appendix are based on linkwork applications found while using this technique.

All the applications of linkwork and linkwork in combination with gears and cams have been found in the General and Mechanical section of the Official Gazette. This section contains approximately 800 of each week's 1,000 patents. On the average 2.5 per cent of these 800 General and Mechanical patents contain useful linkwork applications. This means some 20 patents per week are pertinent to this study. These figures are based on the 6-week period from February 21, 1967, through March 28, 1967.

6. First Stage Digestion

After finding a linkwork application, the first step in the digestion of information has been to form a condensed record containing selected material extracted from the Official Gazette. Each linkwork application is recorded by a simplified sketch of the actual structure appearing in the patent drawing. These sketches are made on 5 x 8 inch cards. In this way the links and joints of the mechanism are shown more clearly. From the simplified sketch, the mechanism is drawn using a usual schematic form of kinematic notation. The links are represented by polygons and lines, and the joints by small circles. The links of this kinematic drawing are numbered consecutively as shown in Table 2 of Chapter 5. These numbers are then assigned to corresponding links of the simplified sketch. The types of the joints are indicated on the kinematic drawing. The remaining information extracted from the Official Gazette is composed of the patent number, the class and subclass, the title of the invention, the inventor's name, the inventor's country of residence, the assignee, the location of the assignee, the filing date of the application, the date of issue of the patent. All this information is placed on one side of a 5 x 8 inch card. Examples of these are shown in Figures 3, 4, 5, 6, and 7.

7. Clarification of Terms

A simplified sketch is a necessary part of the digestion process. The outlines of the links are shown in the same positions as they appear in the patent drawing. Details of the links are included when necessary to clarify recognition of the mechanism's operating characteristics and functions. Revolute joints are represented by small diameter circles at the ends of their appropriate links. Hydraulic pairs are drawn in an easily recognizable form. The mechanism's attachment to ground is shown by crosshatching. Examples of these representations are shown in Figure 8a.

The purpose of a simplified sketch is not to change any properties or characteristics basic to the mechanism, but to remove it from the complicating environment of the patent drawing. After this is done, the mechanism's relation to its kinematic notation is much more revealing.

The terms kinematic chain, mechanism, and kinematic notation need some explanation at this point. According to Hartenberg and Denavit (5), "A kinematic chain is an assemblage of parts, or links, connected by pairs." No link is fixed to the ground. The chain is considered closed when all pairs are complete because of mated, or connected elements. Because of a fixed ground link, linkwork applications drawn using kinematic notation can not be called kinematic chains. Their kinematic chains, however, can be easily recognized.

3,306,571
Gate-Valve
Jean Bussi, Sceaux, and M. Lechevallier, Viry-Chatillon, France,
assignors to Commissariat a l Energie Atomique, Paris, Seine, France.
Filed April 27, 1964

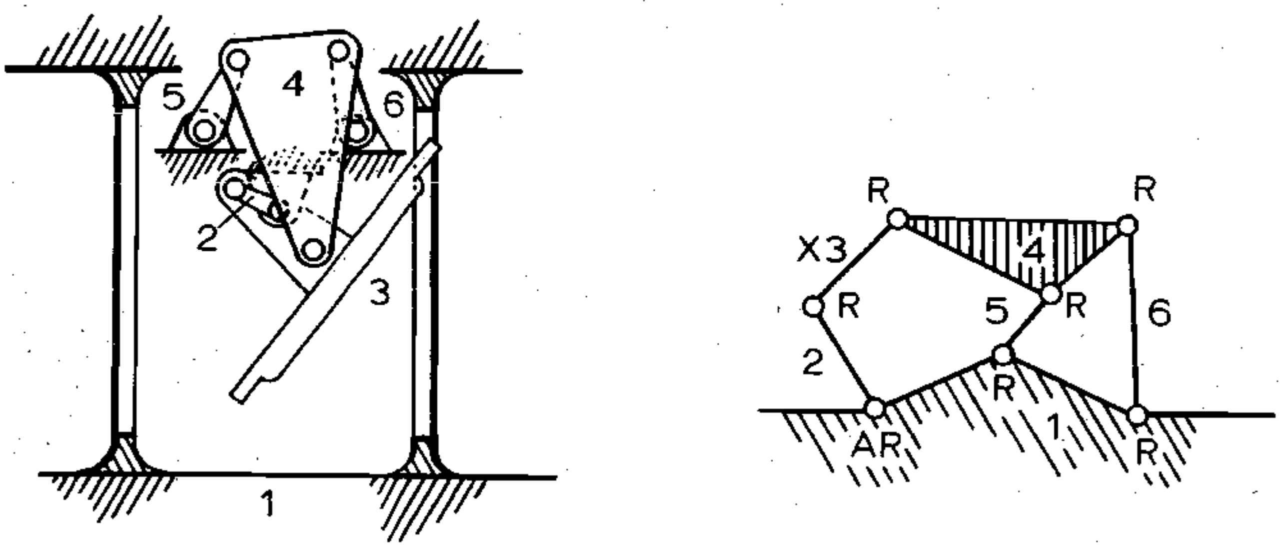


Figure 3. Record of Linkwork Found in Patent No. 3,306,571.

3,310,335
Load Lifting Mechanism
N. E. Shuey, Portland, Oregon
Filed October 13, 1965

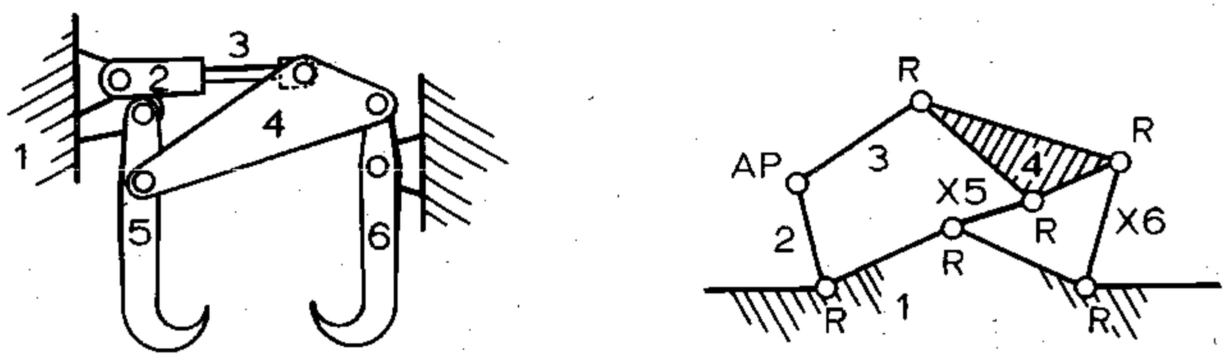
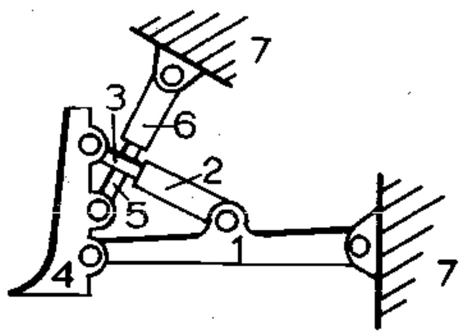


Figure 4. Record of Linkwork Found in Patent No. 3,310,335.

3,184,869
Dozer Hydraulic Tilt and Pitch Control
N. G. Olsen, Highland Park, Illinois
assignor to Allis Chalmers Manufacturing Co.,
Milwaukee, Wisconsin
Filed September 30, 1963



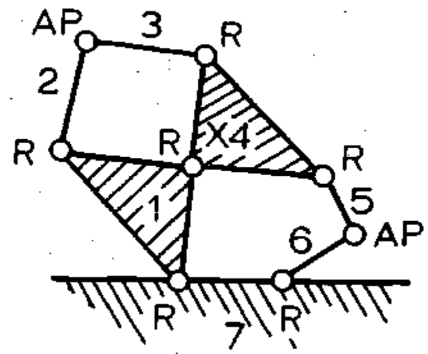


Figure 5. Record of Linkwork Found in Patent No. 3,184,869.

3,203,152
Packaging Machine
R. T. Wilcox, Decatur, Georgia
assignor to the Mead Corporation
Filed March 1, 1962

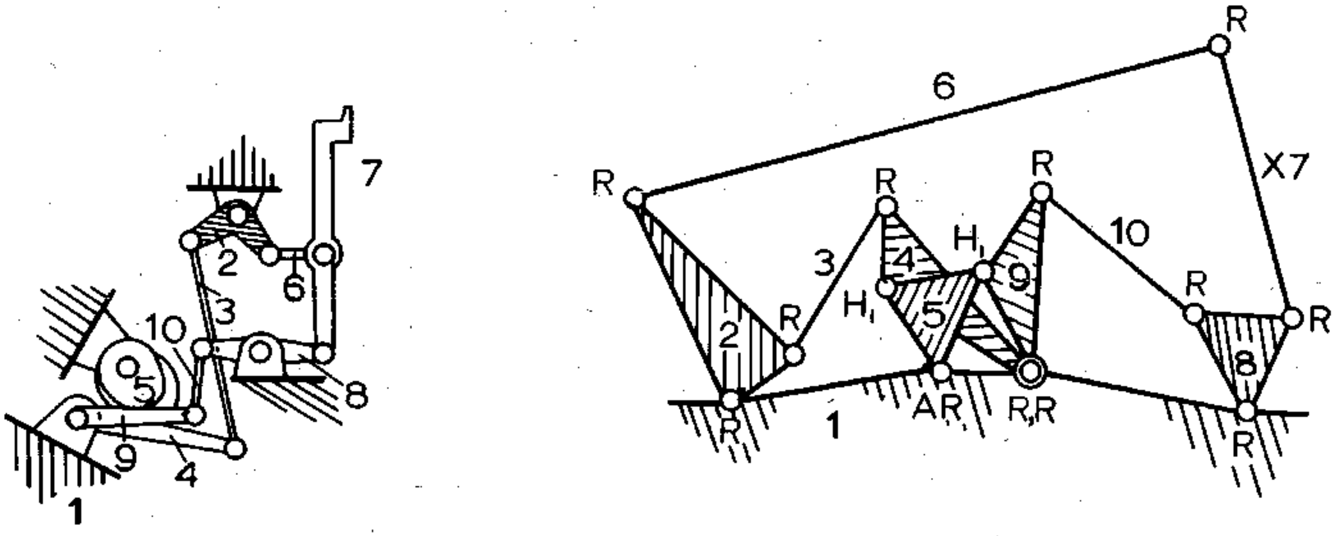


Figure 6. Record of Linkwork Found in Patent No. 3,203,152.

3,306,369
Support for Implements or the Like
W. F. Brewer, Minden, La.
assignor to (by mesne assignments) FMC Corp.
San Jose, California
Filed November 2, 1964

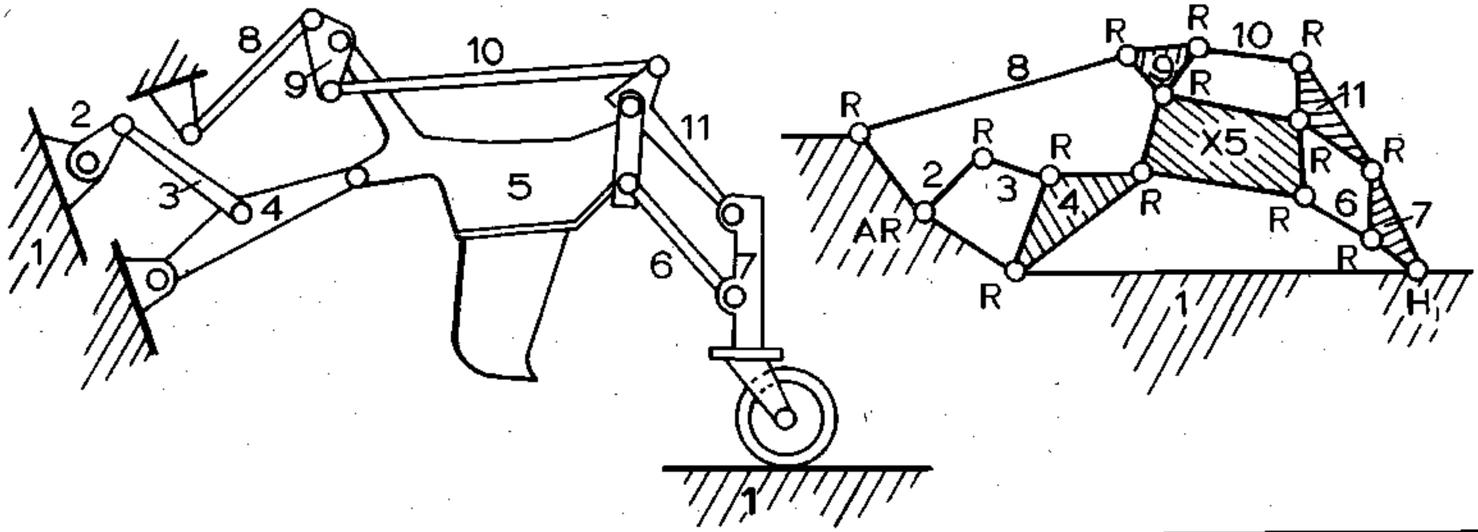
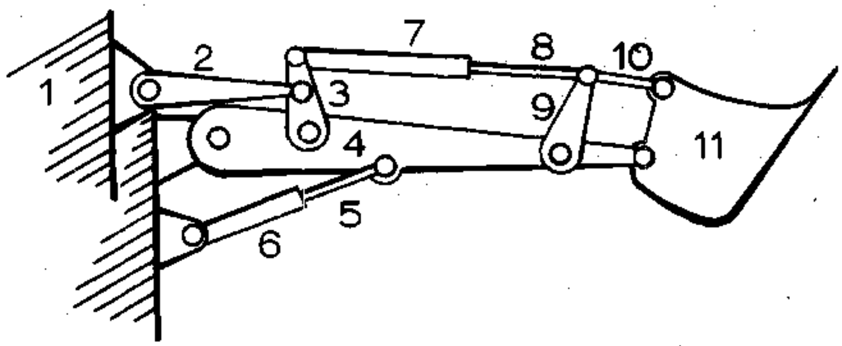
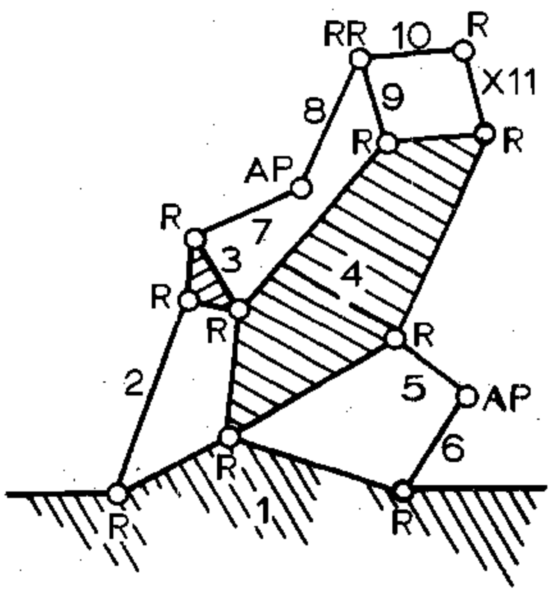


Figure 7. Record of Linkwork Found in Patent No. 3,306,369.



(a)



(b)

Figure 8. Kinematic Representations.

The term mechanism is defined as "a movable closed kinematic chain with one of its links stationary." (5) With regard to this definition, both the simplified sketch and its kinematic representation can be called mechanisms.

The kinematic notation used to represent mechanisms found in the patents has been widely used, with minor modifications, for kinematic chain and mechanism representation. All joints or pairs are represented by small diameter circles. Links containing only two joints, binary links, are shown as straight lines. Links containing more than two joints appear as polygons with the small circles, representing joints, at their vertices. Each polygon is crosshatched for clarity. The ground link is drawn as a crosshatched figure whose sides do not close. All links are numbered. The numbers of the binary links are placed beside the lines representing them. The numbers of links shown as polygons appear within the crosshatched figure. Only letters are used in labeling joints. R is used for a revolute pair, P for a prismatic pair, and H with the appropriate subscript represents a higher pair. The subscript stands for the degrees of constraint of the higher pair and can be a 1 or a 2. A higher pair imposing one degree of constraint or allowing two degrees of freedom is represented by H_1. Two degrees of constraint or one degree of freedom is represented by H_2. An H_2 pair, a revolute pair, and a prismatic pair all allow one degree of freedom. Two H_1 pairs are shown in Figure 6. Davies (2) has pointed out the advantages of associating the input motion of a mechanism with a pair or joint instead of a link. He describes such a pair as an actuator pair. The advantages of this method are discovered when considering an actuator pair not attached to the ground link. Both hydraulic cylinders of Figure 5 are examples of this type of arrangement. In each case an arbitrary decision must be made concerning which link, the piston or the cylinder, should be associated with the input, while there is no question which pairs are actuator pairs. Following these ideas, an actuator pair will be noted by preceding its designating letter with the letter A. An output link will be represented by preceding its designating number with the letter X. Examples of all the above notation are shown in Figure 8b.

CHAPTER IV

FUNCTION VOCABULARY

The United States patents, being an accumulated record of engineering design experiences, have provided a rich source of linkwork applications. The main reason for collecting and digesting these applications has been to determine the functions that they are capable of performing and the uses that can be made of them. In this way kinematic chains and their possible functions can be correlated. Such a correlation would be an aid for the designer practicing type synthesis by indicating the tasks that could be performed by specific kinematic chains. This would suggest the most appropriate linkwork design for a particular task. The linkwork design could in turn be compared with non-linkwork solutions to select the most suitable design approach for the final device. A method of correlating mechanisms, functions, and kinematic chains has been developed by using a function vocabulary. An explanation of that function vocabulary is the object of this chapter. Reuleaux has given encouragement to such an approach involving mechanisms found in practice.

> The thorough understanding of old mechanisms, however, is even more important than the creation of new ones. It is indeed astonishing to how small a depth the methods hitherto used have penetrated into their real nature, and how incompletely known therefore are most of the mechanisms in common use. (15)

1. The Basic Approach

Established techniques of information storage and retrieval contain many useful suggestions for the development of a function vocabulary system for correlating mechanisms, functions, and kinematic chains. A description of certain of these techniques used with documents will be necessary for a complete understanding of the paths of development involved.

One of the simplest methods of indexing the subject content of documents is to extract important words from the text of the document itself. The desirable controls on indexing are to provide a list of common words to be avoided (such as <u>of</u>, <u>and</u>, <u>if</u>, <u>some</u>, and similar ones with little indexing value), to exclude synonyms, and to provide cross references for related terms. The search tool is usually an alphabetical list of the terms used to date, including an indication of the documents associated with each term (1).

An early formalization of this type of approach was the Uniterm Coordinate Indexing System, first proposed in 1952. Vocabulary control was not stressed in the early systems and it was even suggested that the indexer not be required to create and maintain a list of approved Uniterms. The Uniterm approach was developed and initially operated as a manual system (1).

Single-word concepts or ideas (e.g., <u>methane</u>, <u>transistors</u>, <u>B-47</u>) usually make up the basic words in the Uniterm system although multiple-word units are used (e.g., <u>human engineering</u>, <u>Indian Ocean</u>, <u>surface-to-air missiles</u>). The indexer writes out a list of words from the text that he believes are representative of the contents of the document. Uniterm sequence, or the relationship of one to another, is not considered. Each Uniterm is of equal value, and no indexing terms are subordinated or related to any other terms (1).

Stated operating procedures used with Uniterm systems suggest that each document to be indexed be given a unique number (a serial or accession number) and that number be used throughout the system to represent the document. Searching is done by translating the search question into specific Uniterms that represent the substance of the search request. For example, in searching the information file for documents that discuss the human engineering of display systems, the searcher would look for the document numbers common to the two Uniterm units <u>human engineering</u> and <u>display</u>. Search for and access to the appropriate documents can take a wide variety of forms because any basic method of subject indexing, such as the Uniterm system, can be used in conjunction with almost any method of coding, notation, or display.

Bourne (1) has suggested that although there is no precise way to show that a method of indexing becomes more powerful as an increasing amount of control is exercised over the growth and use of the indexing language, this seems intuitively to be true. Such control also seems to correspond to the order of increasing intellectual effort expended by the indexer. If this intellectual effort were used in composing a mechanism function vocabulary of function designators, the logical extension of the previously mentioned techniques of information science would be to use these mechanism function designators as Uniterms in an information storage and retrieval system. The function designators would be used to index and classify digested linkwork applications found in the patents. These mechanisms and their kinematic chains would be placed in the information store in the same manner as the documents discussed previously. Such a system would accomplish the task of correlating mechanism functions with kinematic chains and be a help to the designer as an aid to type synthesis. The functions performed by all kinematic chains of the stored linkwork applications would be readily available. Also in searching for appropriate mechanisms, the designer could use as many function designators as apply to his specific problem.

2. Evaluation of Present Methods of Mechanism Function Designation

The efficiency of an information storage and retrieval system depends primarily upon the indexing and classification techniques used in its development. Coding and display methods would have little effect on how well the original scheme organized a collection of information.

For the system at hand it is the choice of the proper function designators to use in the mechanism function vocabulary which will dictate the effectiveness of the entire system. Before deciding on the best approach to follow in choosing these critical vocabulary terms, it will be well to examine previous designations of mechanism function.

Linkwork mechanisms have long been considered and classified in terms of their ability to transform motion. These motion transforming capabilities of the four-bar linkage were first recognized and separated into the three categories of function generation, path following, and plane positioning. The three categories have since been extended to describe the output motions of mechanisms in general and given the names function generation, path generation, and motion generation (3).

The first of these, function generation, has been referred to as a subset of one-dimensional motion (3). In the function generation case, one-dimensional motion occurs when the output link is separated from the ground only by one lower pair and is oscillatory either in the rotary sense (swinging) or translational sense (reciprocating). The output link's position at any time can be completely described by one parameter or coordinate. In the case of the four-bar linkage a unique relation exists between the coordinates describing respectively the input and output link positions. Plots of the output coordinate versus the input clearly reveal this "functional" relation. The term "function generation" was first used in describing this type of motion transformation. The extended use of the term is given more meaning when considering a mechanism having two or more inputs. In such a case the output from a link connected to the ground by only one lower pair would exhibit the combined effect of the inputs from the two or more actuators, but would still be expressed by the one coordinate describing the output link.

Path following or generation has been referred to as being a "two-dimensional" output motion (3). Such a designation reflects the need for two coordinates in describing the position of the path following point at any instant in time.

Plane positioning or motion generation has been referred to as being a "three-dimensional" output motion because the description of the position of a body is involved rather than that of a point (3). Two coordinates determine the position of a point in the body but a third is needed to give the angular relation between a designated line in the body and a fixed reference line.

These categories of output motion classification find useful application during the dimensional synthesis stage of design involving techniques in which the number of coordinates specified for the output link directly affects the design approach chosen. They lead to ambiguities, however, when used as function designators for existing linkwork applications. Because of their dependence upon the synthesis technique employed by the designer, applying these three categories after the fact to a linkwork application sometimes involves an arbitrary choice.

Function generation can usually be uniquely recognized in applications, but path generation and motion generation present difficulties. Both are indicators of the portion of the output link being considered. Only one point of the output link is considered when dealing with path generation. The output link as a whole is of concern in the case of motion generation. When analyzing some linkwork applications, it is found that only the designer himself can indicate the portion of the output link that was involved in his design criteria. In these cases function classification according to path generation or motion generation categories becomes a matter of arbitrary choice.

This discussion does not mean to imply that the function generation, path generation, motion generation categories are of no use as mechanism function designators. A large number of specific applications are very usefully classified in this manner. It is the use of such a technique as a general all-inclusive approach that leads to unsatisfactory results. Function designators must be arrived at in a different manner.

A second type of function designation can be applied where a specific mechanism is concerned. This type of designation involves a kinematic description of the mechanism such as "a 15° input rotation is transformed into a 45° output rotation with an increasing velocity ratio." Unfortunately such descriptors can only be applied to a mechanism for which the dimensions of the links are known. This information is not given in linkwork applications found in the patents. Also, during the type synthesis phase a designer's thoughts are not detailed enough to use such specific function designators.

The kinematic terms used with the two methods of function designation mentioned thus far exist on two levels. One, composed of categories dividing linkwork applications into three large divisions is too broad; in the other, very specific terms are used to describe dimensioned linkwork mechanisms. The most useful terms would seem to lie on a middle level between the broad and the specific. Such terms are not used in present kinematic practice. They have been discovered using a different approach.

Before continuing, one clarification needs to be made. Since function designating terms are to be used in connection with mechanism applications found in the patents, it might seem possible to use the written matter of the patents to select these terms in the same way that Uniterms are chosen from the text of a document. It has already been explained in Chapter III that the claims are of little use as function indicators. The title of the invention, however, has not been considered as a source of terms. This descriptive designation does not usually apply directly to the linkwork application because the linkwork is rarely the main object of the patent. Another drawback of the title stems from its method of generation: The title is more of a formality than a conscious attempt at a condensation of a patent's uses. It is arbitrarily selected by the inventor and his patent attorney.

Sometimes this selection is even made from a list of examples of previous titles. Nevertheless, both the title and the claims of a patent are of some help: They do give general indications of a linkwork's functions or clarifications of its operating characteristics so that the proper function designators can be chosen.

3. The Function Vocabulary

There are definite properties that the mechanism function designators used with a function vocabulary should possess. Some involve their use by the designer, and others are needed for the proper operation of the information storage and retrieval system. Many of these properties would still be required if similar system techniques were applied to any design discipline.

Ideally the terms used as mechanism function designators would apply to the idea stage of design. They should be able to correspond directly to the task-related thoughts entering the designer's mind while he is searching for an approach to a problem solution. The function designators should incorporate in themselves the necessary kinematic concepts for proper correlation with existing mechanisms and kinematic chains, as well as be clear in their relation to the tasks encountered in practice. Ambiguities in applying the function designators must be held to a minimum. This type of control must work two ways; first in assigning function designators to linkwork applications, and second in expressing search questions in terms of the same vocabulary of function designators. To be used as Uniterms in a storage and retrieval system, the function designators must be of equal value and require no special ordering in presentation. Their number must be large enough that the coverage of mechanism functions produced by the necessary combination of search requests is of appropriate size to be most useful. The vocabulary must be expandable when necessary. Finally, the function vocabulary and the system must be able to be used effectively by the designer.

The function designators that have been chosen for the function vocabulary satisfying these requirements are composed of the words used for ideas. These ideas are the ones which might enter the designer's mind during the planning stages of an approach to a problem solution. They directly correspond to the idea stage of design, being the ideas themselves. Such ideas possess both the needed kinematic and task related concepts that function designators must contain. While still being planning ideas, they also represent mechanism functions. If a mechanism were needed for "lifting," the term itself conveys the necessary information for unique designation needed in a function vocabulary. "Grasping," "supporting," and "scooping" can represent the planning ideas as well as the necessary function designators.

Terms such as these would not be Uniterms in the strict sense of coming from the text of a document, but they would be used in an information storage and retrieval system in the same manner. Any number of function designators could be used to make the search question as specific as necessary for the location of appropriate mechanisms or kinematic chains. The ambiguities encountered using these function designators are only those associated with the ideas the designer has concerning his problem. The number of function designators used in the vocabulary should directly correspond to the number of ideas used by designers in expressing their needs. New ideas should be added as function designators with the growth of the information file containing digested linkwork applications. The function designators corresponding to the linkwork applications found in connection with the patents so far will now be listed:

1.	Absorbing	(Damping)
2.	Advancing	
3.	Aiming	see also Steering
4.	[By Friction]	
5.	Clamping	see also Grasping, Locking
6.	Clipping	(Cutting) see also Squeezing
7.	Contacting	(Touching)
8.	Converting	... provisions for an environmental change such as the positioning of pontoons for an amphibious vehicle
9.	Coordinating	... associated with mechanisms controlling more than one output link
10.	Crushing	(Mashing, Pressing)
6.	Cutting	(Clipping)
11.	[Cycling]	... the continuous repetitive operation of a mechanism with mobility one
1.	Damping	(Absorbing)
12.	Digging	see also Scooping
13.	Direction-Changing	
14.	Dispensing	
15.	Dumping	(Pouring)

16.	Duplicating	(Reproducing)
17.	Ejecting	
18.	Elevating	(Raising)
19.	Engaging	
20.	Equalizing	
21.	Extending	
22.	Forming	
23.	Grasping	... associated with the"tongs" type of movement
24.	Holding	(Retaining) see also Latching
25.	Indexing	
26.	Inserting	
27.	Latching	see also Holding
28.	Lifting	... associated with the movement of bodies external to the mechanism see also Supporting
29.	Locating	... associated with the positioning of bodies external to the mechanism
30.	Locking	see also Latching
31.	Opening	
10.	Mashing	(Crushing, Pressing)
32.	[Parallel]	... the angular relation of the output link with respect to ground remains constant
33.	Path Following	
34.	Plane Positioning	
35.	Plugging	(Sealing)
36.	Polishing	

15.	Pouring	(Dumping)
10.	Pressing	(Crushing, Mashing) see also Sealing
37.	Propelling	
38.	Pulling	
39.	Radial Positioning	see also Swinging
18.	Raising	(Elevating) ... associated with the movement of output links which are implements; plows, scraper blades, etc. see also Lifting
40.	Ratcheting	
41.	Reciprocating	
42.	Releasing	
16.	Reproducing	(Duplicating)
24.	Retaining	(Holding)
43.	Scooping	see also Digging
35.	Sealing	(Plugging) see also Pressing
44.	Squeezing	see also Grasping, Forming
45.	Steering	see also Aiming
46.	Stopping	
47.	Stretching	(Tightening)
48.	Supporting	see also Lifting
49.	Suspending	... thought of in terms of separating a vehicle from the ground
50.	Swinging, Single	... the output link is attached to ground by one lower or H_2 pair
51.	Swinging, Multiple	... more than one case of Single Swinging

52. Symmetrical

53. Tamping

54. Throwing

47. Tightening (Stretching)

55. Tilting

7. Touching (Contacting)

56. Translating

57. Twisting see also Swinging

58. Unsealing

59. Vibrating

The numbers listed with the function designating terms correspond to the coding numbers used with retrieval techniques explained in the next chapter. Some of the terms are listed with the same number. This is done in cases for which the shades of meaning between the function designators do not justify unique representation in the numerical code designation. In such cases the terms are left in alphabetical order in the function vocabulary. Beside each of these terms, the remaining terms of the group are written. Terms which do justify unique representation, but are closely related in meaning to other function designators, will be followed by the words see also and the related terms. Clarifications of vocabulary terms are added when necessary.

New function designators may be added to the vocabulary by assigning them a coding number and placing them in the vocabulary in alphabetical order.

In many situations rules of grammar have been used for clarifying ideas. Professor Dwight Baumann of M.I.T. gave witness to this after working on a project with a short due date for the government concerning high-speed ground transport. During this study the project's participants were made to realize the problems involved with the accumulation and organization of ideas. In order to work with the necessary ideas more effectively, they used rules of grammar to categorize them. These categories were as follows:

Concepts - Nouns

Attributes - Adjectives

Functions - Verbs

Compatibility - Conjunctions

Portions of the same technique have been used with the organization of ideas for the function vocabulary of this chapter. Terms applying directly to mechanism functions have been expressed as present participles, an adjective form of the verb. This is the reason for the <u>ing</u> ending of these terms. Mechanism modifiers or attributes are listed as adjectives. These are the terms enclosed in brackets in the function vocabulary. Both the present participles and adjectives have the same weight when used in the storage and retrieval system.

CHAPTER V

CODING AND STRUCTURAL ANALYSIS

The basis for a correlation of mechanism functions, kinematic chains, and linkwork applications has been developed. The usefulness of this correlation as an aid to type synthesis depends in part upon its presentation to the designer. The construction of a proper presentation by using coding and display techniques from information science is the subject of this chapter.

1. Importance of Proper Coding and Display Selection

The statement was made in Chapter IV that any basic method of subject indexing can be used with almost any method of coding, notation, or display. Among such coding and display methods are computerized techniques. Such mechanized techniques would have advantages, besides speed, over a manual system by providing input and output facilities in remote locations from the computer used for the information store. Whether computerized or not, the proper functioning and performance of the retrieval system still has its basis in the intelligent organization of the information file. Bourne (1) has emphasized this by the following statement:

> The highly mechanized file systems need at least as good a file organization as the manual systems. Otherwise, the machine system may have the dubious distinction of making mistakes 1,000 times faster than the manual system.

After choosing and developing the most desirable method of file organization, the question of coding the individual file items for storage and processing by manual or by machine methods is of secondary importance (1). It is hoped that a computerized application of the present system will be undertaken in the near future. However, during the development stages it has been much more worthwhile to use manual system coding and display techniques.

2. The Manual Card System

A manual edge-notched card system was chosen as the storage and display medium. Such manual card systems have been in use for many years and have proven to be very flexible for information storage and retrieval applications. They are especially useful for two types of jobs. The first is sequence sorting to arrange data into a logical order. The second and more meaningful for the purpose at hand is selective sorting. Records can be selected which fall into a single specific category (direct selection), or which fall into a specified combination of categories (multiple selection) (1).

The cards of such a system are coded by notching their edges. The notches are imposed on pre-punched pilot holes. This is done so that the code position is no longer surrounded by card stock, and the card can not be supported by a needle which is passed through that code position. Searching is performed by passing a needle through the appropriate pilot hole in a bundle of cards and allowing the notched cards to fall free from the unnotched cards. Friction between adjacent cards creates a problem, and the cards must sometimes be separated or vibrated to ensure that no notched cards are kept from falling (1).

In order to provide enough coding positions a special edge-notched card was used. This was an 80-column IBM card pre-punched with the character I in each of its columns. This character provided a row of holes at the top and bottom of the card that could be used for notching and needling in the same manner as other edge-notched cards (1).

As an aid in searching the cards a wooden frame was constructed: This is shown in Figure 9. By using 0.0468 inch diameter metal rods the desired number of coding positions can be needled simultaneously.

Two decks of top and bottom punched IBM cards, approximately 2.25 inches thick, were used as guides for the needles. One deck was bolted to the inside front of the frame and the other to the inside back. To answer a search request, a deck of coded cards is placed upright between the guides. The far left and far right coding positions are never notched so that all the cards can always be supported by rods through these holes. The appropriate number of metal rods are slipped through the coding positions to correspond to the search request. The far left and far right rods are then removed, and the wooden frame is lifted to allow cards exactly corresponding to the code request to drop out.

Information useful to both the designer and kinematician is available from the index cards of digested linkwork applications. This information includes the function designators which describe the application, the number and types of inputs actuating the mechanism, the number of links, the kinematic chain and the inversion used, the number of higher pairs, the total number of joints, the inventor's country of origin, and the industry in which the application is used. The designer's interest in this information will be dictated by the depth of his background in kinematics. The kinematician will be interested in all.

The edge-notched cards received in response to a search request

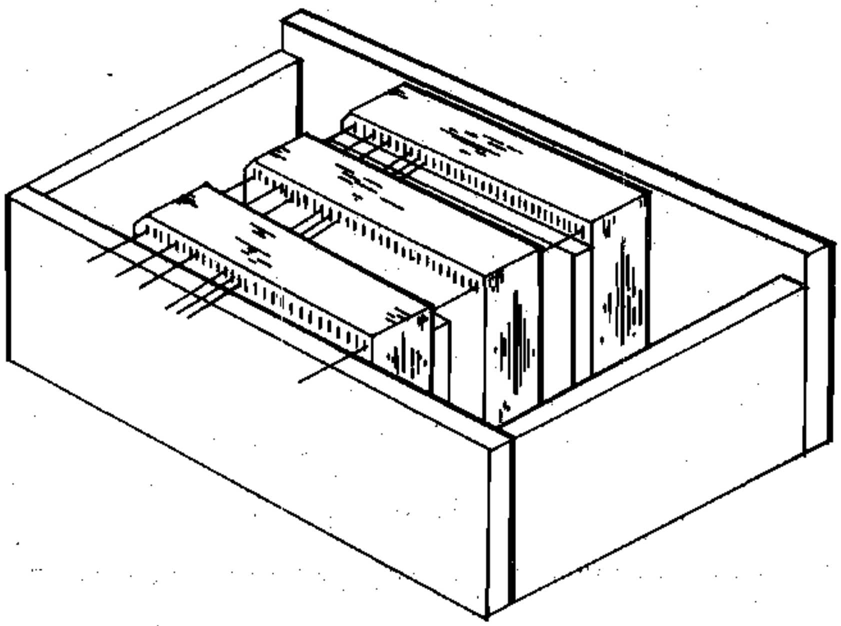


Figure 9. The Manual Card Selector.

contain an identification number. The identification number of each card represents the digested linkwork application from which it was coded. The applications are kept in order according to their identification numbers. The results of a search request can be quickly changed from a group of identification numbers into the corresponding linkwork applications by simply looking through the application file. The identification number itself is the number of the patent in which the application was found. If more than one application is found in a patent, decimals are added to distinguish them. An example of three applications from the same patent would appear as 3,308,976.0; 3,308,976.1; and 3,308,976.2.

Two types of coding have been used with this manual card system. Both methods require that code numbers be punched directly into the card. The code numbers correspond to the information obtained from each digested linkwork application.

The first method is used to code the function designators of the function vocabulary. One code position is assigned to each function designator. In this way the file can be searched for any number of designators simultaneously, without the occurrence of false drops. "False drops" are items located in response to a search request which have no relevance to the search question. They occur because the indexing pattern of a particular item to be coded is not unique, and can be synthesized from several different combinations of descriptor code patterns (1).

The second method of coding uses a modified 7-4-2-1 scheme to save space on the card. Only four holes are needed to represent any number between 0 and 14, although the code is normally used for the digits 0 to 9. When used without modification, the code can cause ambiguities and an excessive number of false drops to result. For example, a field with no punches can represent either missing data or a zero digit. Also, the 1 hole must be punched with the coding of every 1, 3, 5, or 8; consequently, if the cards were searched for the 1 digit, a single needle passed through the 1 hole would cause all the cards punched with a 3, 5, or 8 to drop out. This situation is illustrated in Figure 10. A single needle pass in the 4 hole would cause cards notched with 5's and 6's also to be selected (1).

By adding two more coding positions, the 7-4-2-1 method can be used without ambiguity and false drops. A 0 hole position is added to punch the zero digit, and an SF position is used to indicate that a punched digit is being used as a "single figure" and not as a part of a sum of digits. Thus, simultaneously needling the SF hole and the 1 hole will select only the cards punched with the value 1 and ignore sums involving 1, such as 3, 5, and 8. False drops are thus eliminated (1).

3. Coding of the Function Vocabulary

The numbers used to code the function designators are those listed beside them in Chapter IV. Each term is given a unique code position along the top of the edge-notched cards. The coding of a linkwork application used for Dumping, Lifting, Raising, Scooping, and Supporting is shown in Figure 11. There are additional coding positions along the top of the cards to allow for growth of the function vocabulary.

4. Coding of Kinematic Chains and Inversions

During the process of digesting each linkwork application, a kinematic representation of its structure is drawn. The corresponding

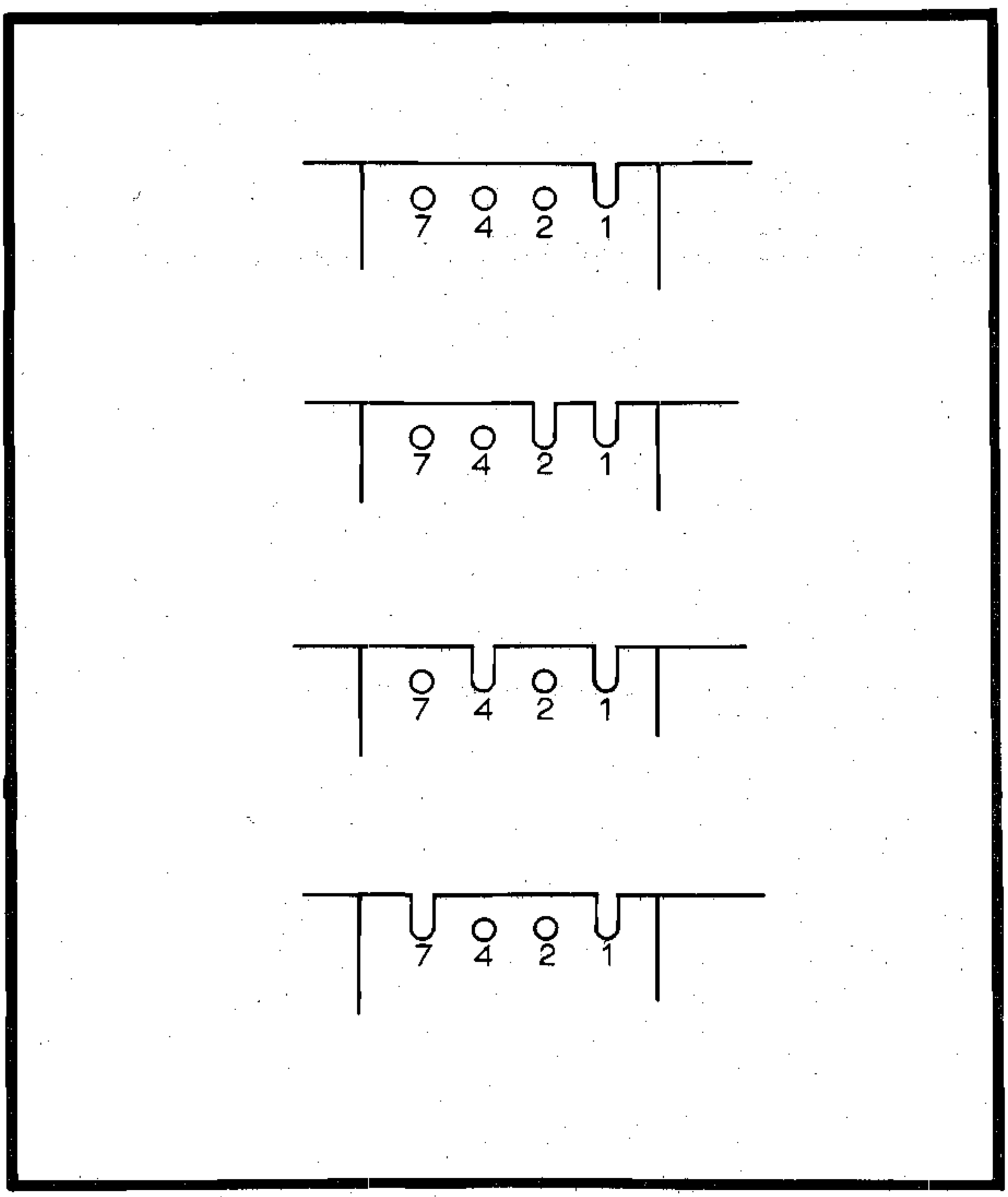


Figure 10. False Drops with the 7-4-2-1 Scheme.

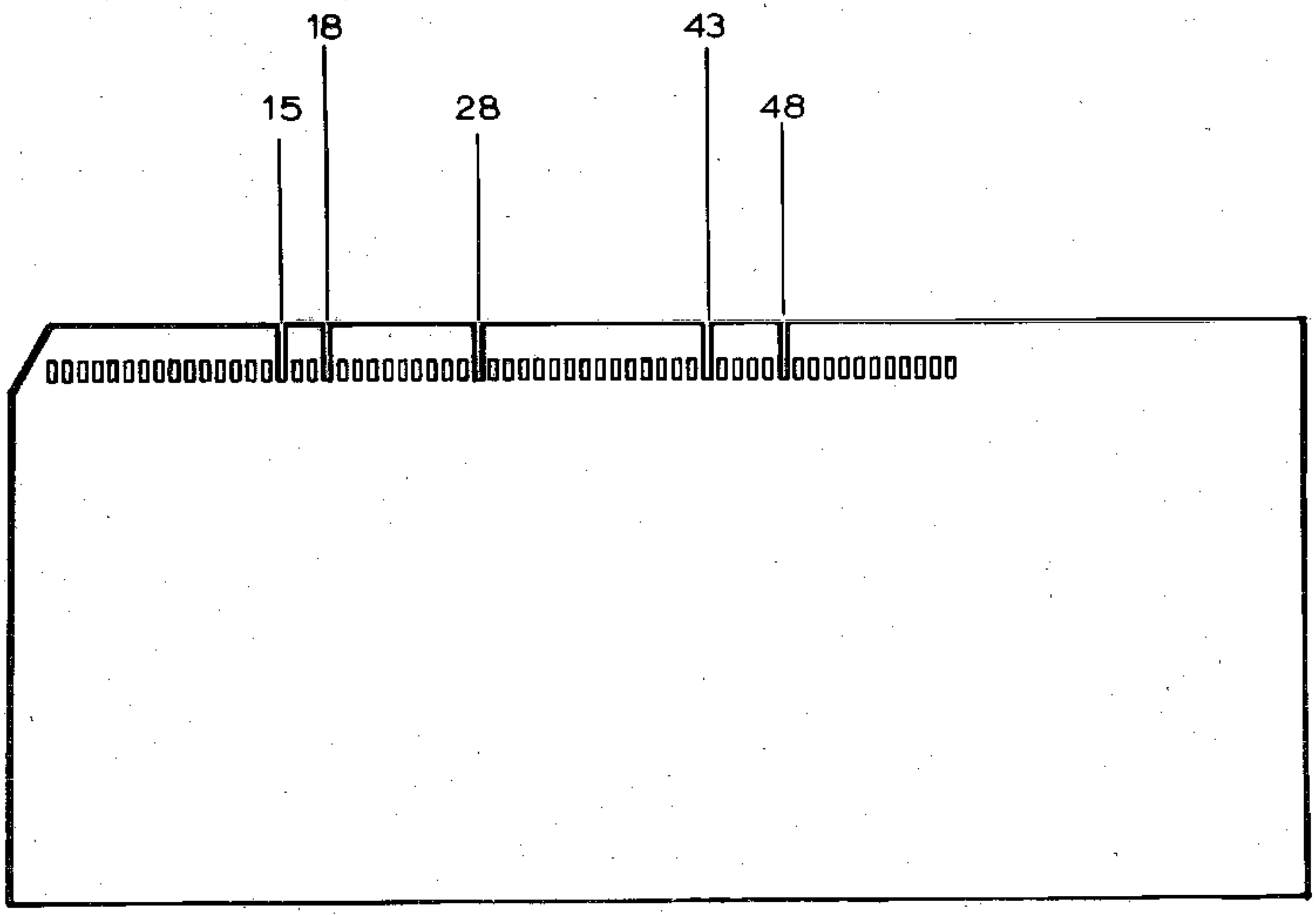


Figure 11. Function Designator Coding.

kinematic chain and its inversion are coded on a manual card by using the SF-7-4-2-1-0 scheme.

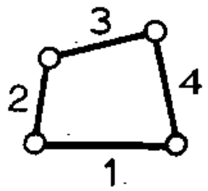
For the system to operate, a selected set of kinematic chains are drawn and their links are numbered. These are shown with their corresponding code designations in Table 2. The manual cards are coded from this table. Five digits are needed to represent each kinematic chain and its inversion. The first two digits give the number of links in the chain. A four-bar would be represented by 04. The second two digits specify the type of kinematic chain in a group having the same number of links. A Stephenson six-bar would appear as 0602. The last digit gives the particular inversion of the mechanism by specifying the number of the ground link. An application is shown in Figure 12. For cases in which different links may be used as ground and produce the same inversion, the ground link with the lowest number is coded.

The first nineteen kinematic chains of mobility one are shown in Table 2. Represented there are one four-bar, two six-bars, and 16 eight-bars. Of the chains having mobility two, the four seven-bars have been shown (4). The kinematic chains containing more than eight links are found in relatively few applications in the patents compared to the number of types that exist (35 nine-bars and 210 ten-bars). Due to this fact, the detailed coding of chains with more than eight links has not been included in the present treatment. They are coded only by the number of links they contain, and a search question specifying this is sufficient for their retrieval.

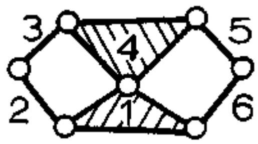
5. Coding of Inputs and Joints

Davies (3) has suggested that the actuator or source of motion of

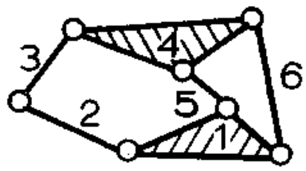
Table 2. Kinematic Chain Codes



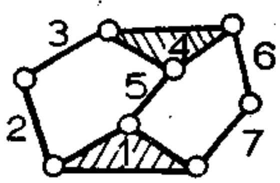
0401_



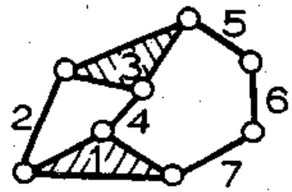
0601_



0602 _



0701_



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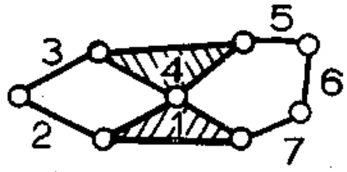

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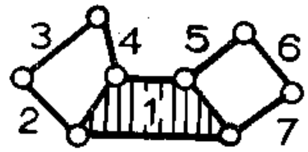

0704_

Table 2. Kinematic Chain Codes
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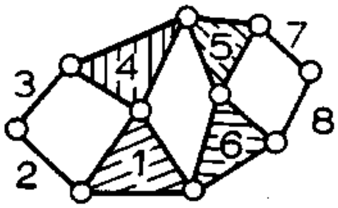

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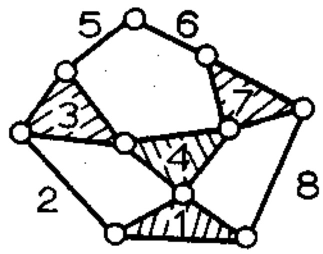

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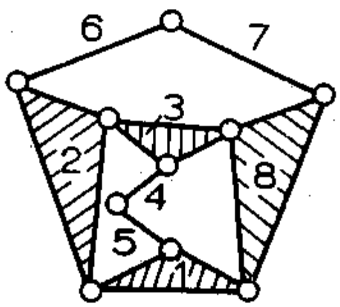

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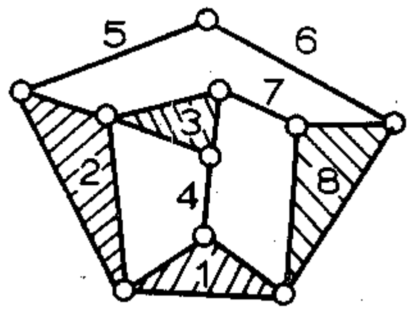

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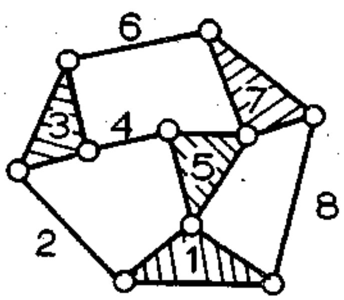

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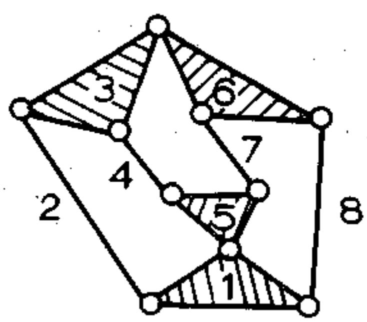

0806_

Table 2. Kinematic Chain Codes
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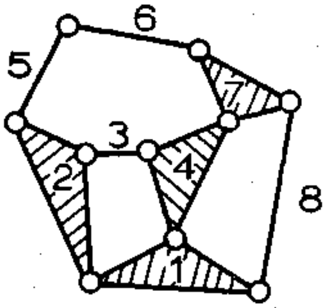

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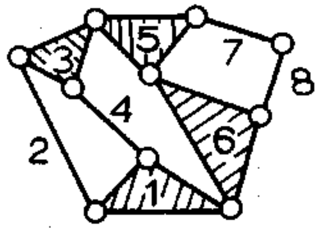

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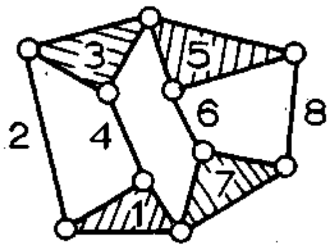

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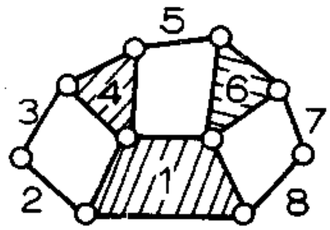

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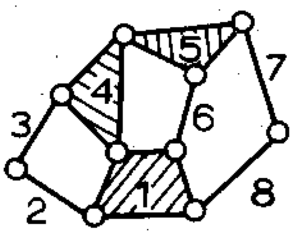

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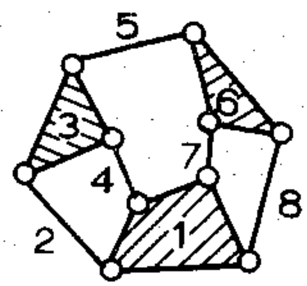

0812_

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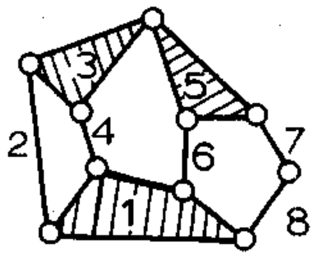
(Continued)



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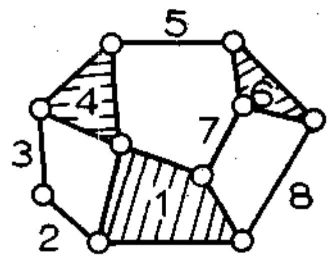

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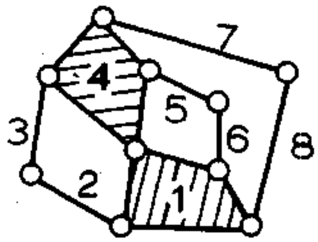

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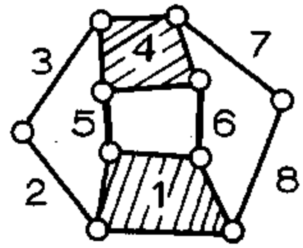


0816_

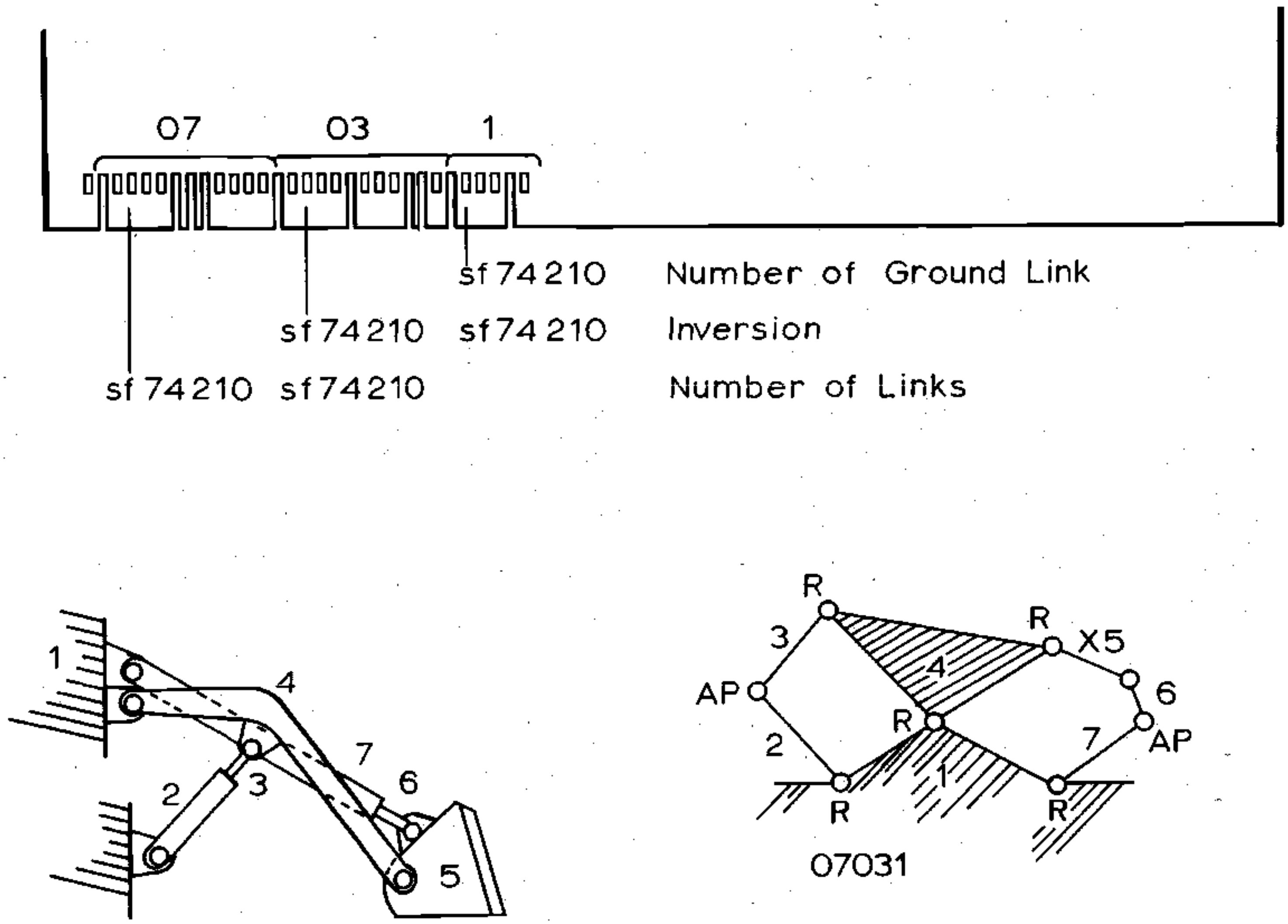


Figure 12. Coding of Kinematic Chains and Inversions.

a planar mechanism is nearly always one-dimensional. As in the case of a one-dimensional output, the position of the input actuator at any instant can be described by one parameter. Examples would be an angular displacement or a translational displacement along a path. Davies (3) also states that one-dimensional motion can be said to be either progressive or oscillatory. These ideas have been adopted for the designation of mechanism inputs used in coding the manual cards. A progressive rotation is called a <u>rotary</u> input. Oscillatory angular motion is described as <u>swinging</u>, and oscillatory translation is designated <u>reciprocation</u>.

The total number of inputs, the type of each input, and the total number of each type are indicated for every linkwork application. Code numbers are punched in the cards by using forms of the SF-7-4-2-1-0 scheme. The zero code position is omitted for representing the total number of inputs since all mechanisms require at least one. One notched code position is used to indicate the presence of rotary inputs. The code position is not notched in case of their absence. This position is followed by SF-7-4-2-1-0 to indicate the number of rotary inputs. Swinging and reciprocating inputs are represented in the same manner with their own code positions. The format for this part of the card is shown in Figure 13.

The total number of joints a linkwork application contains are indicated by two digits, one to represent units and the other for tens. Each is coded by the SF-7-4-2-1-0 technique. The total number of higher pairs is represented by one digit. Coding is done in the same way. Figure 13 gives an example of the technique.

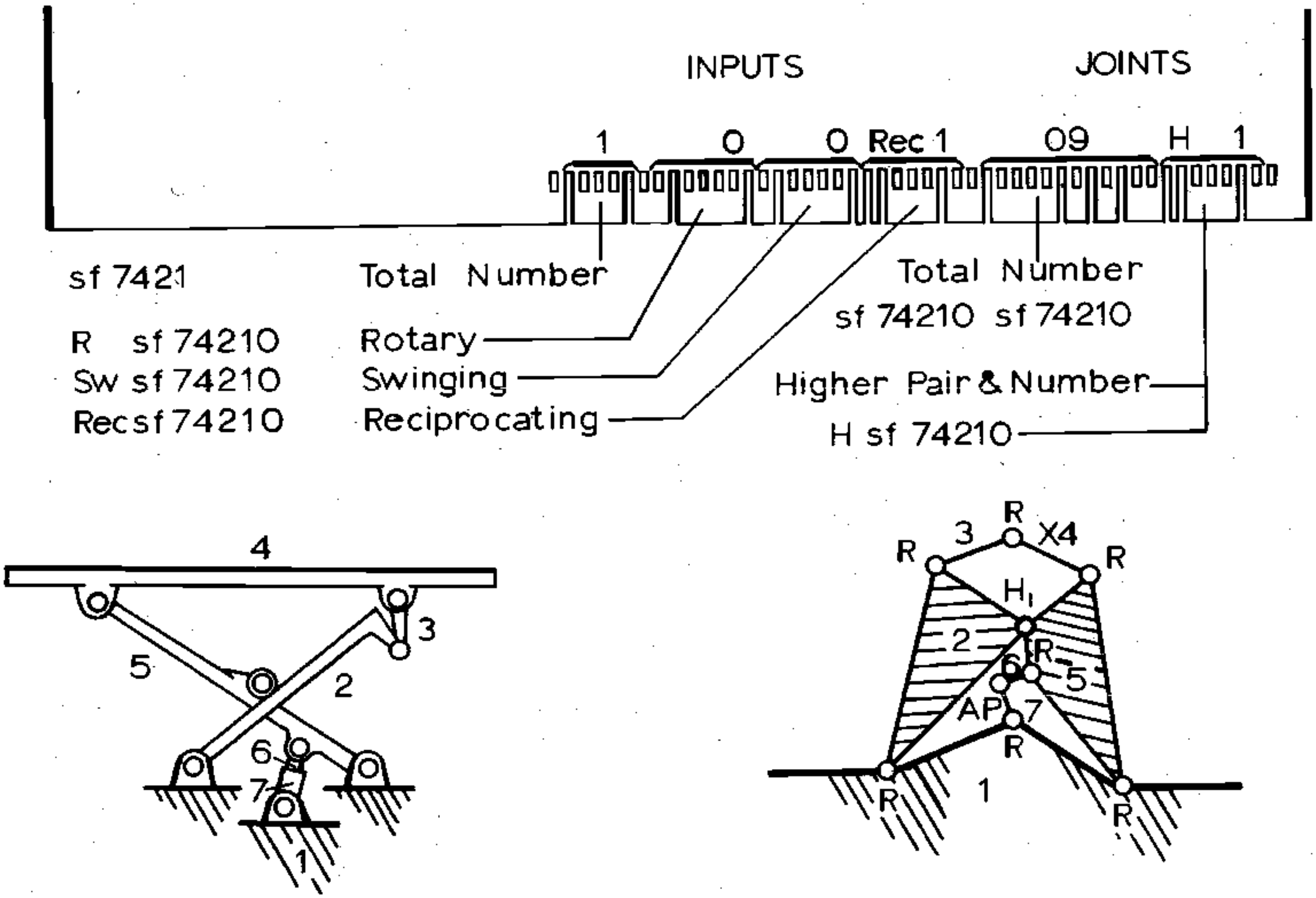


Figure 13. Coding of Inputs and Joints.

6. Coding the Inventor's Country of Origin

Besides the kinematic information already coded, a digested linkwork application contains the country of origin of its designer (the patented article's inventor). These countries are coded using two digits and the SF-7-4-2-1-0 technique. The countries represented thus far are listed in Table 3. New countries are placed in alphabetical order in the table. The old countries keep their original code numbers while the new countries are given consecutively higher ones. Because of the large amount of information already coded, the inventor's country of origin and the industry to which the application belongs must be placed on a separate card. The nature of the items to be coded allows this to be done. The inventor's country of origin and the industry using the linkwork design can be considered separately from the joints, inputs, kinematic chains, and function designators with the least amount of searching inconvenience. Figure 14 illustrates the new card's format.

7. Industry Coding

A list of designators is used to indicate the industry in which a linkwork design is most likely to find application. These industries and their two digit codes are given in Table 4. The SF-7-4-2-1-0 representation is used for each digit.

In a few cases a particular design may be used by more than one industry. To eliminate false drops each industry is assigned an individual coding position as was done for the function designators. This technique is allowable because of the extra space of the new card. Figure 14 illustrates this approach. Additional industries may be

Table 3. Inventor's Country of Origin

Code Designation	Country
01	Australia
02	Belgium
03	Canada
04	Denmark
05	England (Great Britain)
06	France
07	Germany
08	Ireland (Eire)
09	Italy
10	Japan
11	Norway
12	Switzerland
13	United States of America

13 United States of America

11 Earth Moving Eguipment

8 Construction

1 Agricultural Equipment

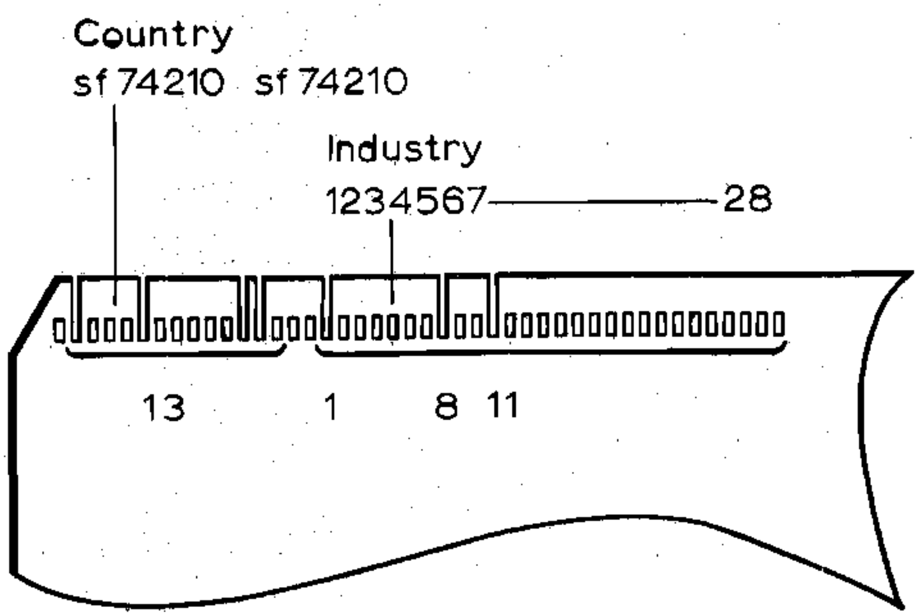


Figure 14. Inventor's Country of Origin and Industry Coding.

Table 4. Industry To Which the Linkwork Design Belongs

Code Designation	Industry
1	Agricultural Equipment
2	Aircraft
3	Atomic Reactor Hardware
4	Automobile
5	Boating Equipment
6	Carpet
7	Cleaning (of vehicles)
8	Construction
9	Consumer Products (low cost)
10	Dredging
11	Earth Moving Equipment
12	Electrical Equipment
13	Furniture
14	Hand Tool
15	Hospital Equipment
16	Household Appliance
17	Laboratory Apparatus
9	Low Cost Consumer Products
18	Lumber
19	Material Handling Equipment
20	Material Processing Tool
21	Military Vehicle
22	Mining
23	Packaging
24	Photographic Apparatus
25	Printing
26	Railroad Equipment
14	Tool (hand)
20	Tool (material processing)
27	Toy
28	Trailer
7	Vehicle Cleaning

alphabetized into the list of Table 4 and assigned code numbers starting with 27.

8. System Improvements

A computer application to the manual card system may take two forms. One would parallel document retrieval and require the manual search of a secondary file to produce the linkwork applications. The other would store the complete linkwork applications in computer memory and give answers to a search request in its print-out.

With both systems a computer program could be made available and supplementary cards sent to the user as the collection of linkwork grew. Similar techniques can now be used with a manual system. The completely computerized approach, however, offers some unique advantages. Since all the information can be given by the computer output, search requests could be made and satisfied from remote input-output facilities or inquiry consoles. Also, because it does not have to produce a unit record, the totally computerized system would have the potential to give specific answers to search requests. This could mean that instead of receiving all the information about a linkwork application, the user could be given selected information pertinent to his search request.

The unit record aspect of the linkwork applications makes possible one improvement in the mechanization of the manual card system. Several methods of microfilm unit-record storage are available to which the secondary file of digested linkwork applications can be converted. One simple technique appropriate for this purpose makes use of an aperture card. In principle an aperture card is just a file card with one or more frames of microfilm mounted in a window cut from the interior of the card stock. It is very useful for applications in which each image or small group of images represents a separate file item to be filed, retrieved, and handled as a unit (1).

The most common aperture card is of the same dimensions and card stock as a conventional IBM or machine tabulating card. A single frame of 35mm film fits in the aperture. These aperture cards can be handled on conventional tabulating equipment. Relatively simple manual equipment is available to cut single 35mm frames from a film roll and mount them in the card. Most microfilm viewing equipment can handle the aperture card (as well as roll microfilm). Equipment has been available for a long time to easily reproduce the image from one aperture card onto the film of another (1).

Such a unit-record storage device makes possible the mechanized filing and retrieving of a complete linkwork record. The film could contain all information previously recorded on the 5 x 8 card, including the mechanism's kinematic representation and the simplified sketch.

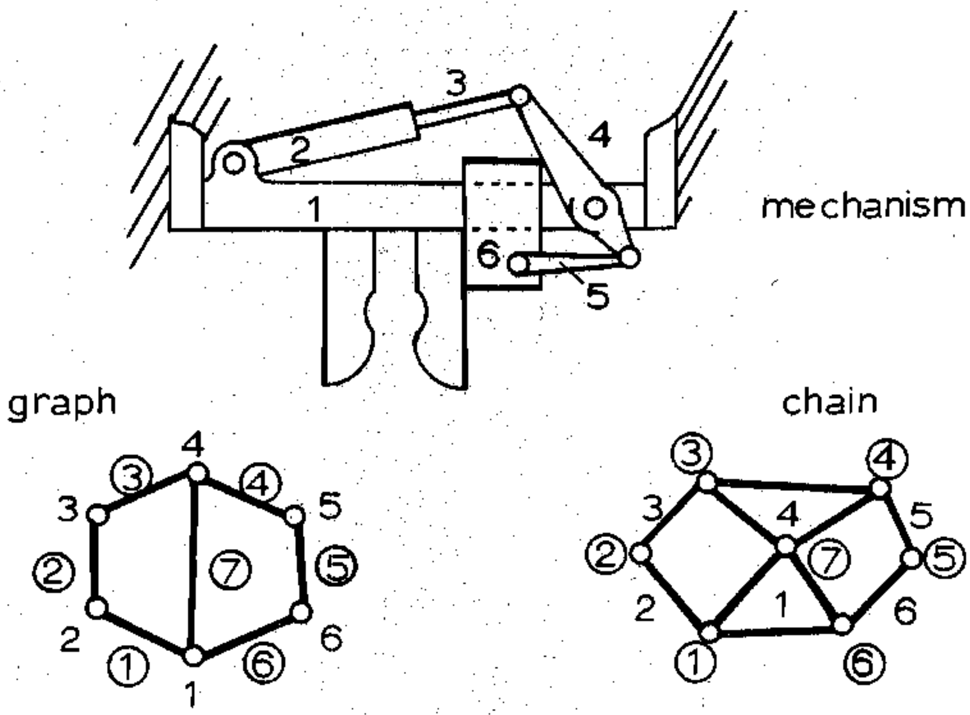
9. Computerized Applications

The main problems involved in developing a completely computerized system are the kinematic representation and simplified sketch. Both involve the storage of image material. The simplified sketch is a graphic image which indicates to the designer the way the links of a kinematic chain should be arranged and proportioned. This is necessary in order for a similar mechanism to have the properties described by the function designators. One method employed for the digital storage of an image is to approximate the image with a rectangular matrix of discrete, equal-area elements, each element having a quantized intensity or shading corresponding to that of the original image. Things such as the number and size of matrix elements and the amount of tone scale preserved determine the accuracy of the approximation. Such a technique could prove useful for representing the simplified sketches of linkwork.

The work of Dobrjanskyj and Freudenstein (6) has shown the successful application of an incidence matrix approach for representing kinematic chains. The method uses the kinematic graph of the kinematic chain. The structure of a kinematic chain is completely defined by its kinematic graph, in which the links are represented by vertices, the joints by edges, and the joint coupling of links corresponds to edge connection between vertices. A mathematical representation of the kinematic graph is made using a vertex-edge incidence matrix. This is a rectangular matrix whose general element, m_{ij}, is 1 or 0 according as the i^{th} vertex is, or is not, incident at the j^{th} edge. Figure 15 illustrates the graph of a kinematic chain and its vertex-edge matrix.

The vertex-edge matrix can easily be stored in a computer. Since the matrix completely defines its corresponding kinematic graph, the structure of the kinematic chain will also be defined.

The matrix can also be adapted to include the statement of the different types of joints, output links, and ground links which are present. For example, elements in the vertex-edge matrix associated with a hydraulic actuator or a higher pair could be denoted by an appropriate single-digit code number. Distinguishing numbers could also be used for ground and output links. A separate matrix, however, must be



Vertex-Edge Incidence Matrix

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 1 & 1 \\ 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 0 \end{bmatrix}$$

Figure 15. A Kinematic Graph and Its Vertex-Edge Matrix.

used to designate the set of joints and the set of links. Dobrjanskyj and Freudenstein (6) have developed a computer program capable of sketching a kinematic graph from its incidence matrix. Using FORTRAN II and an IBM 7094 computer, ten-link kinematic chains can be sketched in about 1½ minutes. Further developments could make possible the sketching of kinematic chains belonging to stored linkwork applications, with joints, output links, and ground links being indicated.

An incidence matrix approach can be used for the structural comparison of kinematic chains. About 3½ minutes of computer time using the IBM 7094 were needed for a structural comparison of two ten-link F=1 chains (6). With future developments it could be possible to compose search requests for kinematic representations with joints (including higher pairs), output and ground links, and inputs indicated.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

1. Present Work

A linkwork storage and retrieval system based on a vocabulary of mechanism functions offers promise as an aid to type synthesis. The further development of the system and its use with practical applications will prove its final worth. The following conclusions, however, have been reached after developing the initial stages of the manual card system as presented in this thesis:

1. The United States patents provide one effective source of examples of the linkwork which is used by practicing designers.

2. Mechanisms having a mobility of two appear in the patents in sufficient number to warrant more fundamental research.

3. Prismatic pairs in the form of hydraulic actuators find more frequent application in linkwork design than had been expected.

2. Future Work

The following recommendations are made for future study:

1. There is still much that needs to be done in extending the function vocabulary dealing with linkwork. It is extremely important that good judgment be exercised in including or rejecting new terms and revising old ones. Revision and improvement must be continually practiced until the most effective vocabulary is formed. Yet the terms must not be so extensively defined or altered, so that the typical designer

can not approach the index and use the terms which seem natural to him.

2. A substantial number of linkwork records should be found and coded before questioning the adequate and valuable nature of the system. At least 200 more linkwork records should be incorporated into the system before a judgment is made.

3. The function vocabulary approach should be broadened to include mechanisms composed of other construction units besides linkwork.

4. The manual card system should be computerized and the problems involved in the design of a computer file and its structure for searching solved. The system needs to be so designed to answer readily all questions of which the manual system is capable, and search requests for any specific kinematic chain or chain modified by the inclusion of higher pairs.

5. Computer-aided graphics appears a promising area for it has potential to solve the problems of representing kinematic chains and approximate mechanism proportions.

APPENDIX

DATA CONCERNING LINKWORK FOUND

IN THE UNITED STATES PATENTS

All the following results are based on a search of the United States patents issued in the 6-week period from February 21, 1967, through March 28, 1967.

The search was made from the General and Mechanical division of the Official Gazette issued for the weeks:

February 21, 1967

February 28, 1967

March 7, 1967

March 14, 1967

March 21, 1967

March 28, 1967

The complete patent was referred to when more information concerning the linkwork contained in the patent was needed.

For the 6-week period of patent issues involved, approximately 6,000 patents were reviewed. From this search 121 applications of linkwork were found and recorded. Some specific results are shown on the following pages.

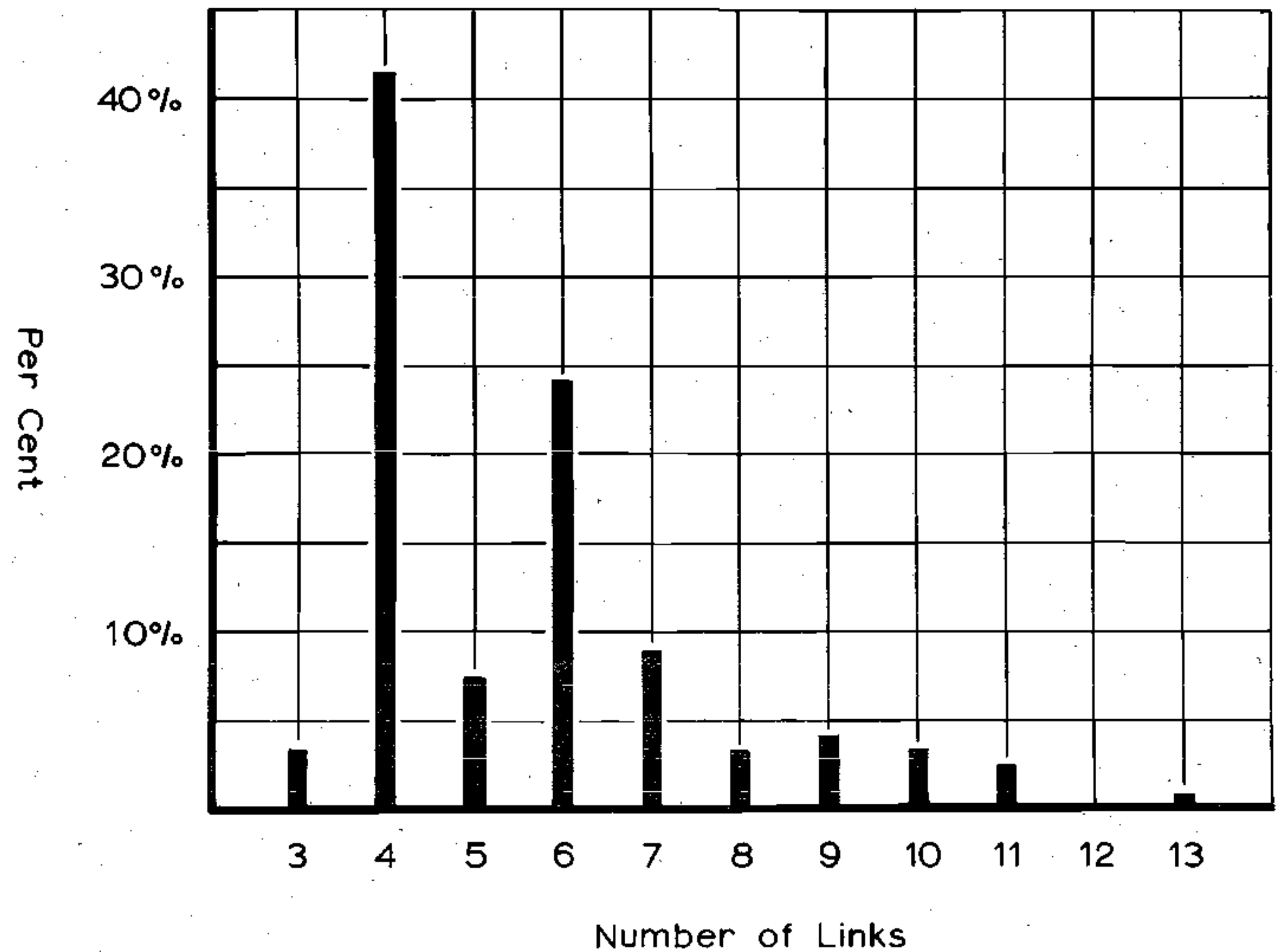
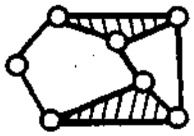


Figure 16. The Percentages of Mechanisms Found Versus the Number of Links in Their Kinematic Chains. (Based on 121 mechanisms in a 6-week period of patent issues.)

Table 5. The Number of Mechanisms Found Having a Specified Number of Links

Number of Links	Number Found	Per Cent of Total
3	4	3.3
4	50	41.4
5	9	7.4
6	29	24.0
7	12	9.9
8	4	3.3
9	5	4.1
10	4	3.3
11	3	2.5
12	0	0
13	1	0.8
TOTAL NUMBER	121	

Table 6. The Occurrence of Six-Bar Linkages

	Watt	18	62.0%
	Stephenson	8	27.0%
	Undesignated (Due to the presence of higher pairs)	3	10.4%
	Total Number	29	

Hydraulically Actuated Mechanisms

Per Cent of the Total Number Hydraulically Actuated	43.8%	(53 of 121)
Per Cent of 4-Bars Hydraulically Actuated	32.0%	(16 of 50)
Per Cent of 6-Bars Hydraulically Actuated	55.2%	(16 of 29)

Mechanism Inputs

Per Cent Having Two Inputs	15.7%	(19 of 121)
Per Cent Having Three Inputs	0.8%	(1 of 121)
Per Cent Having Four Inputs	0.8%	(1 of 121)
Per Cent Having Rotary Inputs	12.4%	(15 of 121)
Per Cent Having Swinging Inputs	33.9%	(41 of 121)
Per Cent Having Reciprocating Inputs (other than hydraulic)	9.9%	(12 of 121)

Table 7. Countries Represented
(Inventor's Country of Origin)

Code Designation	Country	Number Found
01	Australia	1
02	Belgium	1
03	Canada	2
04	Denmark	1
05	England (Great Britain)	5
06	France	4
07	Germany	4
08	Ireland (Eire)	1
09	Italy	1
10	Japan	1
11	Norway	1
12	Switzerland	1
13	United States of America	98

Table 8. Industries Represented

Code Designation	Industry	Number Found
1	Agricultural Equipment	9
2	Aircraft	2
3	Atomic Reactor Hardware	2
4	Automobile	16
5	Boating Equipment	3
6	Carpet	1
7	Cleaning (of vehicles)	1
8	Construction	8
9	Consumer Products (low cost)	4
10	Dredging	1
11	Earth Moving Equipment	12
12	Electrical Equipment	2
13	Furniture	5
14	Hand Tool	5
15	Hospital Equipment	5
16	Household Appliance	2
17	Laboratory Apparatus	1
18	Lumber	4
19	Material Handling Equipment	21
20	Material Processing Tool	7
21	Military Vehicle	3
22	Mining	1
23	Packaging	4
24	Photographic Apparatus	1
25	Printing	1
26	Railroad Equipment	3
27	Toy	2
28	Trailer	3

Table 9. The Frequency of Use of Function Designators

Code Number	Function Designator	Number of Times Used
1	Absorbing	7
2	Advancing	2
3	Aiming	3
4	By Friction	3
5	Clamping	4
6	Clipping	1
7	Contacting	3
8	Converting	3
9	Coordinating	16
10	Crushing	10
11	Cycling	5
12	Digging	1
13	Direction-Changing	3
14	Dispensing	3
15	Dumping	5
16	Duplicating	1
17	Ejecting	2
18	Elevating	14
19	Engaging	2
20	Equalizing	3
21	Extending	5
22	Forming	1

Table 9. The Frequency of Use of Function Designators (Continued)

Code Number	Function Designator	Number of Times Used
23	Grasping	9
24	Holding	2
25	Indexing	4
26	Inserting	2
27	Latching	5
28	Lifting	13
29	Locating	6
30	Locking	11
31	Opening	1
32	Parallel	14
33	Path Following	3
34	Plane Positioning	4
35	Plugging	9
36	Polishing	2
37	Propelling	2
38	Pulling	3
39	Radial Positioning	1
40	Ratcheting	2
41	Reciprocating	15
42	Releasing	1
43	Scooping	1
44	Squeezing	5

Table 9. The Frequency of Use of Function Designators (Continued)

Code Number	Function Designator	Number of Times Used
45	Steering	1
46	Stopping	3
47	Stretching	6
48	Supporting	29
49	Suspending	3
50	Swinging, Single	35
51	Swinging, Multiple	10
52	Symmetrical	9
53	Tamping	1
54	Throwing	1
55	Tilting	2
56	Translating	6
57	Twisting	2
58	Unsealing	8
59	Vibrating	1

Data Recorded
For Each Linkwork Record

Mechanism Function	(from a Function Vocabulary having 59 terms)
Number of Links	
Inversion and Number of Ground Link	
Inputs:	
Total Number	
Rotary and Number	
Swinging and Number	
Reciprocating and Number	
Joints:	
Total Number	
The presence or absence of Higher Pairs and Number	
Inventor's Country of Origin	(13 terms)
Industry To Which the Linkwork Belongs	(28 terms)

LITERATURE CITED

1. Bourne, Charles P., "Methods of Information Handling"; John Wiley and Sons, Inc., New York, 1963.

2. Davies, T. H., "An Extension of Manolescu's Classification of Planar Kinematic Chains and Mechanisms of Mobility $M \geq 1$, Using Graph Theory," J. Mechanisms 3 (Summer issue 1968).

3. Davies, T. H., "The Selection of Linkage Mechanisms," Machine Design Engineering, 5, Sept. 1967, pp. 36-42.

4. Davies, T. H., and F. E. Crossley, "Structural Analysis of Plane Linkages by Franke's Condensed Notation," J. Mechanisms 1 (1966).

5. Denavit, J., and R. S. Hartenburg, "Kinematic Synthesis of Linkages"; McGraw-Hill, New York, 1964.

6. Dobrjanskyj, L., and F. Freudenstein, "Some Applications of Graph Theory to the Structural Analysis of Mechanisms," ASME Paper No. 66-Mech-24, 1966.

7. "General Information Concerning Patents," U.S. Department of Commerce/Patent Office, 1966.

8. Grodzinski, Paul, "A Practical Theory of Mechanisms"; Emmott and Co. Ltd., Manchester, 1947.

9. Hain, K., Discussion on F. R. E. Crossley, Trans. ASME J. Engr. Industry, 86, Series B, 1 (1964).

10. "How to Obtain Information from United States Patents," U.S. Department of Commerce/Patent Office, 1962.

11. Jones, Stacy V., "The Inventor's Patent Handbook"; The Dial Press, New York, 1966.

12. Kessler, K. O., and Norman Carlisle, "The Successful Inventor's Guide: How to Develop, Protect, and Sell Your Invention Profitably"; Prentice-Hall, Inc., Englewood Cliffs, N. J., 1965.

13. Manolescu, N. I., "Une méthode unitaire pour la formation des chaînes cinématique et des mécanismes plans articulés avec différents degrés de liberté et mobilité," Revue Roumaine Sci. Techn., Méchanique Appl., 9, 1263 (1964).

14. Manolescu, N. I., "Systématisation et classification des mécanismes moteurs plans articulés, a deux degrés de mobilité "total" ($M_3=2$) et "partiel" ($M^P=2$), "Revue Roumaine Sci. Techn. Méchanique Appl., 10, 999 (1965).

15. Reuleaux, F. (translated by A. B. W. Kennedy) "The Kinematics of Machinery"; Macmillan and Co., London, 1876.

16. "The Story of the United States Patent Office," Pharmaceutical Manufacturers Association, 1965.

17. Tuttle, S. B., "Mechanisms for Engineering Design"; John Wiley and Sons, Inc., New York, 1967.

18. Willis, Robert, "Principles of Mechanism"; 2d ed., Longmans, Green & Co., Ltd., London, 1870.